NEW

Exploration | Solar System | Deep Space | Space Science | Future Tech

All About Space Annual

Digital Edition

Everything you want to know about our galaxy and beyond

Welcome to the All About Space Annual

Even with the COVID-19 pandemic, which ground planet Earth to a halt, 2020 has been an incredible year in the world of space and astronomy. Countries around the world, from China to the UAE and more, have launched brand new space missions. Anniversaries have been celebrated in the stratosphere. Scientific discoveries have expanded our knowledge more than ever before. In the **All About Space Annual 2021** we look back at some of the highlights of the past year and bring you the best of **All About Space** from the past 12 months. We round up all that's been happening at Hubble for the last 30 years, and find out what the future holds for this iconic space telescope. Wondered what you'd sound like if you could speak on another world? Discover how your voice would change on the planets of the solar system. Meet the people pioneering private intergalactic travel, including the man hoping to send the first British rover into space in 2021. Last but not least, explore some of the amazing inventions that could launch in the next five years. Enjoy!


FUTURE

All About Space Annual

Future PLC Quay House, The Ambury, Bath, BA1 1UA

Bookazine Editorial
Editor **Alice Barnes-Brown**
Senior Designer **Adam Markiewicz**
Editorial Director **Jon White**
Senior Art Editor **Andy Downes**

All About Space Editorial
Editor-in-Chief **Gemma Lavender**
Art Editor **Jon Wells**

Cover Images
NASA; ESO; ESA; Adrian Mann; Tobias Roetsch; Getty Images

Photography
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Advertising
Media packs are available on request
Commercial Director **Clare Dove**
clare.dove@futurenet.com

International
Head of Print Licensing **Rachel Shaw**
licensing@futurenet.com

Circulation
Head of Newstrade **Tim Mathers**

Production
Head of Production **Mark Constance**
Production Project Manager **Clare Scott**
Advertising Production Manager **Joanne Crosby**
Digital Editions Controller **Jason Hudson**
Production Managers **Keely Miller, Nola Cokely, Vivienne Calvert, Fran Twentyman**

Management
Chief Content Officer **Aaron Asadi**
Commercial Finance Director **Dan Jotcham**
Head of Art & Design **Greg Whitaker**

Printed by William Gibbons, 26 Planetary Road, Willenhall, West Midlands, WV13 3XT

Distributed by Marketforce, 5 Churchill Place, Canary Wharf, London, E14 5HU
www.marketforce.co.uk Tel: 0203 787 9001

All About Space Annual Volume 8 (ABK34.53)

Future plc is a public company quoted on the London Stock Exchange (symbol: FUTR)
www.futureplc.com

Chief executive **Zillah Byng-Thorne**
Non-executive chairman **Richard Huntingford**
Chief financial officer **Rachel Addison**

Tel +44 (0)1225 442 244

Part of the

All About Space bookazine series

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"My belief is that in future, you will have to live on the moon" Pavlo Tenasyuk, page 76

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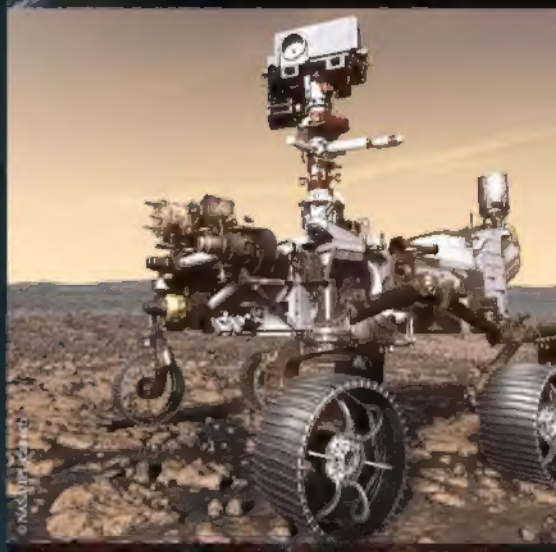
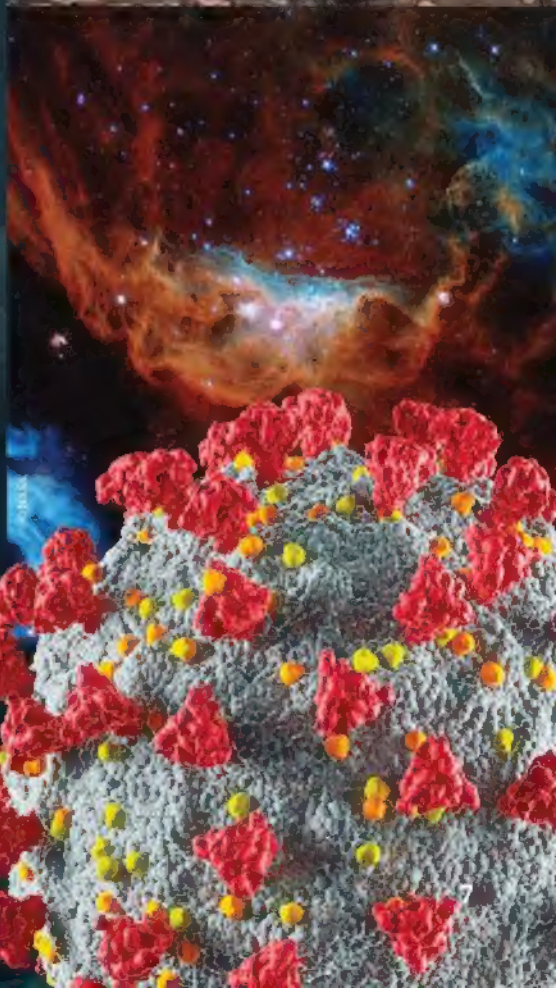




2020: A YEAR IN SPACE

The mission launches, news and discoveries that have made 2020 such an exciting year in space

Reported by Baljeet Panesar

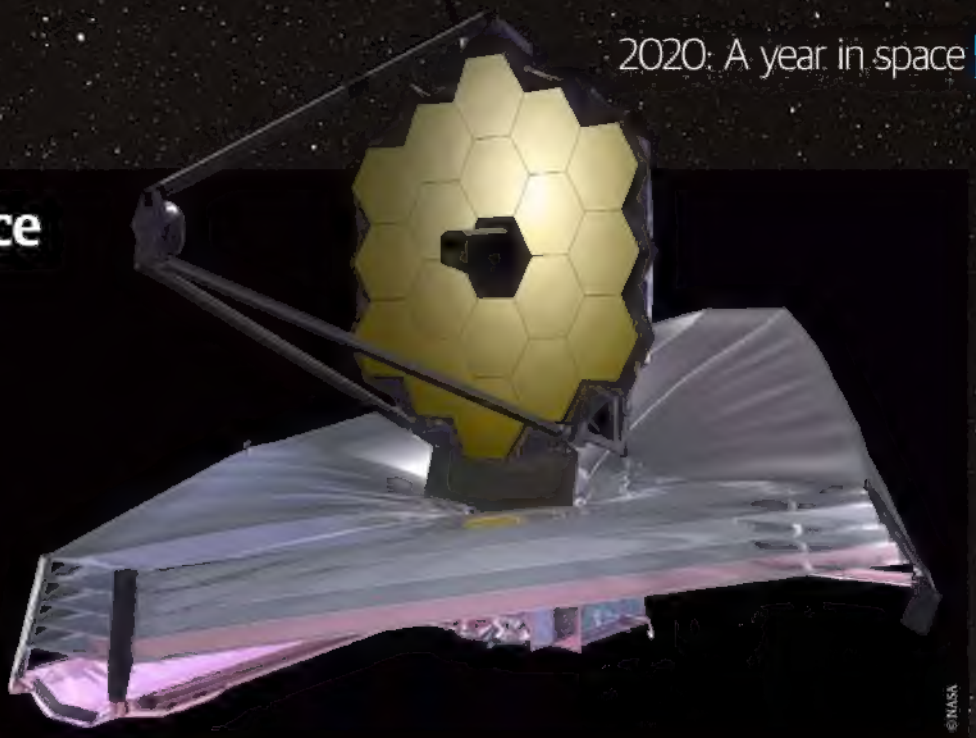
In the midst of a year dominated by the Covid-19 pandemic, it can be easy to forget that 2020 has been an extraordinary year for space exploration and human spaceflight achievements. We've seen the retirement of one of NASA's Great Observatories, the launch of three missions to Mars and SpaceX's first crewed flight to the International Space Station (ISS). We've celebrated the anniversaries of the Hubble Space Telescope, Apollo 13 and Chandrayaan-2, among many others. We've experienced some disappointment, inevitable in space exploration, but we're possibly getting closer to answering the ultimate question: is there life on other worlds?

Our desire to explore, discover hidden worlds and push the boundaries of science addresses the need for us to understand the history of our Solar System and our place within it - and the universe. This year has opened up a new age of spaceflight, and the discoveries that we make from these cosmic endeavours may help us to eventually send humans to the Moon and Mars.

We may be at the start of the decade, but from what we have achieved this year, this decade will continue to surprise and astound us. These achievements have brought space exploration back to the attention of the public, which hasn't been seen since the Apollo era. Here are a few notable achievements from the year.

James Webb Space Telescope

After several years of delays and mounting costs, on 16 July the launch of the James Webb Space Telescope (JWST) was rescheduled once again to October 2021. JWST will be the world's premier space telescope of the 2020s that will complement and expand on the discoveries made by Hubble. JWST's 6.5m (21ft) primary mirror will be used to study the early universe, from the formation of the first stars and galaxies to our Solar System in infrared light. The space telescope will also search for regions where stars are currently forming and the atmospheres of exoplanets for signs of life.



Spitzer retires

30 January

After more than 16 years of studying the Solar System, exoplanets and distant galaxies in infrared, Spitzer's mission was complete and the telescope was decommissioned.

Pale Blue Dot 30th anniversary

14 February

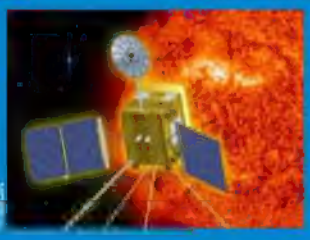
This iconic picture (right) was taken by Voyager 1, about 6bn km (3.7bn mi) from Earth, as it was heading towards the outer Solar System.

ExoMars mission delayed

13 March

The launch of ESA and Roscosmos' Rosalind Franklin rover has been postponed to 2022. The rover will look for signs of past life and study the history of water on the Red Planet.

JANUARY — FEBRUARY — MARCH



Solar Orbiter launch

10 February

On a mission to understand our star's dynamic behaviour, Solar Orbiter will get to within 42mn km (26mn mi) of the Sun's surface in 2022.

Marsquakes confirmed

24 February

Since InSight arrived on Mars it has detected hundreds of marsquakes, believed to be linked to volcanically active regions. Scientists hope that InSight will continue to reveal Mars' interior and how it is changing.

Space junk and Starlink

Throughout the year, SpaceX has launched hundreds of Starlink satellites as part of a mission to create a low-cost, high-speed global internet service. Eventually, as many as 42,000 of these satellites could be in orbit, leading to concerns about space debris.

Currently there are around 34,000 pieces of space junk larger than 10cm (4in). Satellite operators can perform collision-avoidance manoeuvres to avoid damage or destruction from nearby debris. Such manoeuvres are performed thousands of times a year, but this could increase to 67,000 if all Starlink satellites were to launch.

Perseverance's seven minutes of terror

This year, two surface missions have been launched to Mars, but the most dangerous part of their journey is yet to come – the landing. Once a rover enters the Martian atmosphere, it is on its own. This is known as the 'seven minutes of terror'. During this time the rover slows itself from 20,000km/h (12,400mph) to just 2.7km/h (1.7mph) to safely land on the Martian surface. It takes 11 minutes to confirm whether the landing has been successful or not.

55th spacewalk anniversary

18 March

Cosmonaut Alexei Leonov made his historic spacewalk 55 years ago, stepping outside the confines of the Voskhod capsule. His spacewalk lasted just over 12 minutes.

© Getty

Return to the Moon

30 April

NASA selected three companies – Blue Origin, SpaceX and Dynetics – to design landers for the Artemis program to take the first woman and next man back to the Moon in 2024.


© NASA

MARCH — APRIL


© NASA

Apollo 13 at 50

11 April

Launched on 11 April, Apollo 13 was supposed to be the third mission to land on the Moon. After a successful launch, Commander Jim Lovell, Command Module Pilot Jack Swigert and Lunar Module Pilot Fred Haise seemed to be having a smooth flight. But, roughly 56 hours into the mission and 330,000km (210,000mi) from home, the catastrophic rupture of an oxygen tank in the Service Module changed everything.

As a result of the explosion, the lunar landing was abandoned. To conserve their oxygen supply the crew had to turn off all their electrical equipment and move into the Lunar Module, using it as a 'lifeboat'. Although the Lunar Module wasn't designed for three men on a long journey, the crew safely landed back on Earth six days after lift-off.

NASA classified the mission as a 'successful failure', and changed the design of the oxygen tanks for future missions.

Hubble's 30th anniversary

24 April

Back in 1990, NASA and ESA launched the Hubble Space Telescope aboard Space Shuttle Discovery. One day later, Hubble was released into orbit, starting a mission that would revolutionise our understanding of the universe and our place within it.

30 years later and Hubble has surpassed all expectations. It has calculated the age and rate of expansion and acceleration of the universe; monitored storms on planets in our Solar System; found that massive black holes are common in galaxies, investigated the elusive dark matter, and much more.

Hubble will continue to uncover the secrets of the cosmos and capture celestial imagery throughout the 2020s, and it should be joined by the JWST next year.

Life in the clouds of Venus?

14 September

An international team of astronomers have detected a rare molecule that could have a biological origin in the clouds of Venus. The molecule is called phosphine, which on Earth can only be made by microbes or through industrial processes. In theory, chemical processes should destroy the molecule before it can be detected in such quantities.

The astronomers identified phosphine 51-60km (32-37mi) high in the atmosphere. Scientists have long considered the possibility of cloud-based Vesuvian life because temperatures and pressures there are less intense than on the surface. However, the gas may possibly have inorganic origins, including lightning, meteor impacts or volcanic activity. NASA is considering two possible missions to Venus which may help to solve the phosphine mystery.

Chandrayaan-2's first anniversary in lunar orbit

20 August

After one year, Chandrayaan-2 has made 4,400 orbits and mapped 4mn km² (1.5mn mi²) of the Moon. It will continue studying the lunar surface for another six years.


© NASA

AUGUST — SEPTEMBER


© NASA

Most massive gravitational wave source detected

2 September

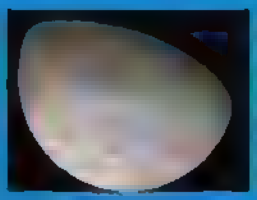
The most massive gravitational wave source detected so far was the result of a black hole merger. Two black holes merged to produce a single black hole with a mass of 142 Suns.


© Alamy

More buried lakes on Mars

28 September

In 2018, the ESA's Mars Express detected a subsurface lake buried 1.5km (1mi) below the ice. Three more smaller lakes have been identified. It is thought that they could be remnants of an ancient ocean.



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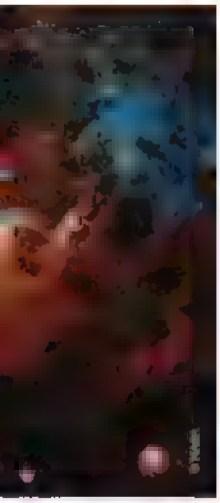
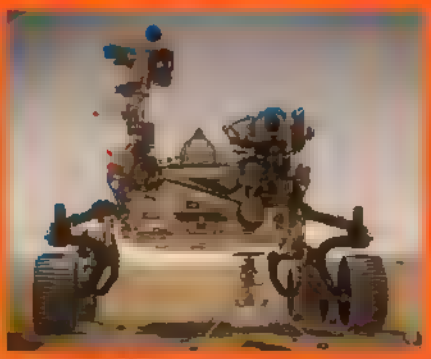


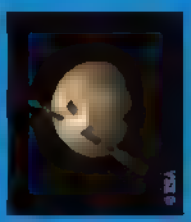
Crew Dragon launch

30 May

After NASA retired the Space Shuttle in 2011, it had relied on Russia and their Soyuz capsule to send American astronauts to the ISS. That changed this year when the Crew Dragon mission marked a return to launching astronauts from American soil. The SpaceX spacecraft carried astronauts Robert Behnken and Douglas Hurley to the ISS, making them the first spacefarers to be launched into orbit by a private company, and marking the start of a new era in human spaceflight.

The mission was a test flight, called Demo-2, and its success means that Crew Dragon can carry more people into space. During the 62 days they spent on board the ISS, Behnken and Hurley completed scientific experiments, spacewalks and outreach events. They completed 1,024 orbits around Earth and travelled over 43mn km (27mn mi). The spacecraft safely splashed down in the Gulf of Mexico on 2 August. The next Crew Dragon mission, SpaceX Crew-1, is expected to launch in November 2020.





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NOVEMBER

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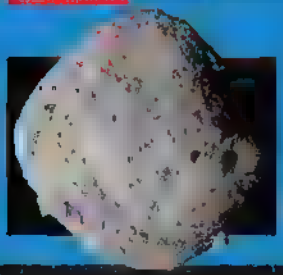


Solar System

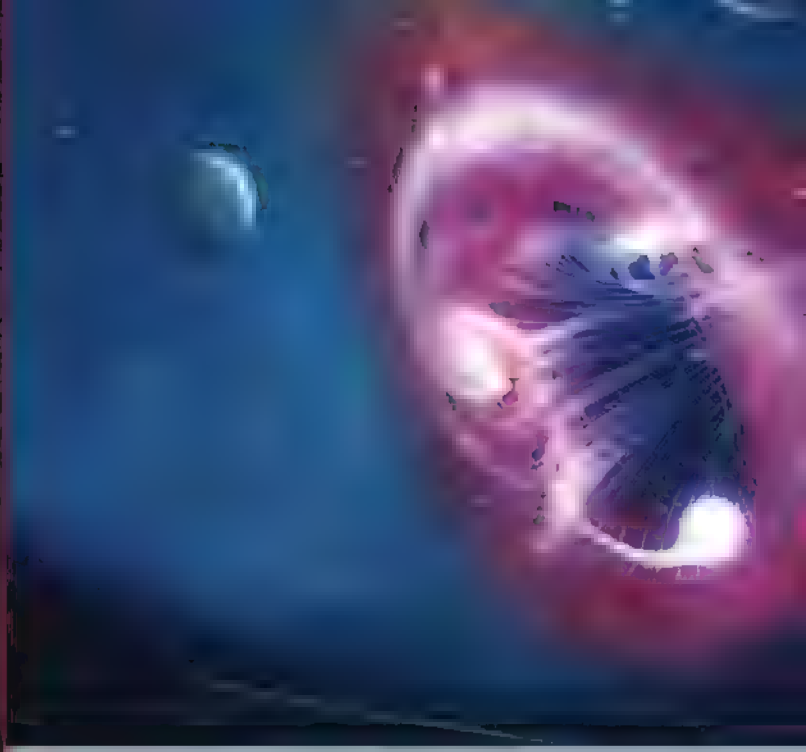
Discover the secrets of our fascinating planetary system

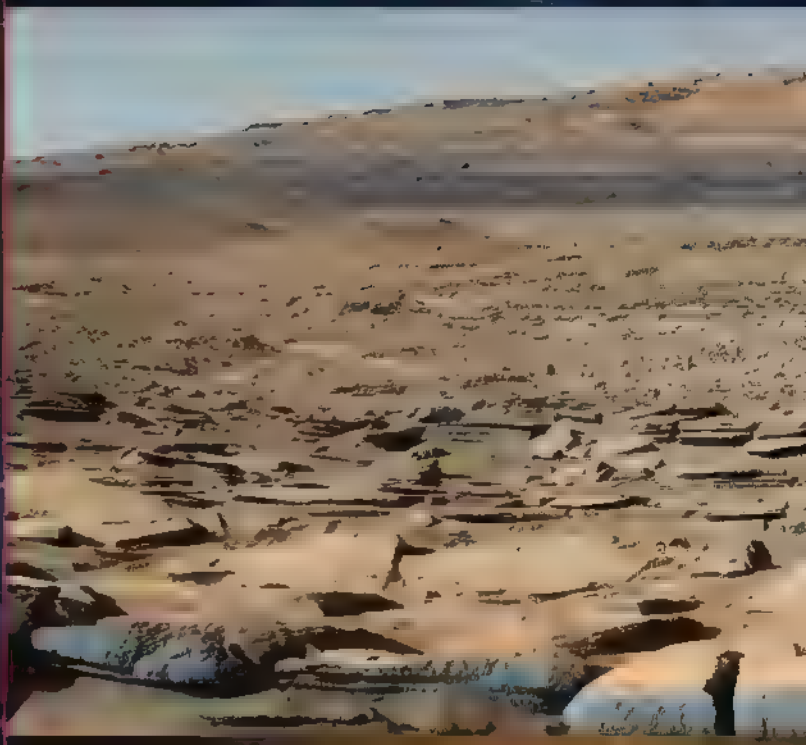
14 **Climate change in the Solar System**
Alongside Earth, our planetary neighbourhood is changing, but it's not for the better... it's for the worse

22 **Solar System's black hole**
As the hunt for a mysterious world at our solar neighbourhood's edge steps up, something more exotic might also fit the bill

30 **What would you sound like on other worlds?**
How would the human voice differ if astronauts were able to talk on other planets?

"Unlike Venus, the Earth will eventually adjust to the increase in carbon. We just may not be around to see it"





CLIMATE CHANGE IN THE SOLAR SYSTEM

Alongside Earth, our planetary neighbourhood is changing, but it's not the first time it's for the worse

Illustrated by Colin Stuart

It's no secret that Earth is in trouble, and it is largely our fault. Since the Industrial Revolution we have been pumping so much carbon dioxide and other greenhouse gases into the atmosphere that our planet is rapidly warming. The race is on to keep the rise to under 1.5 degrees Celsius (2.7 degrees Fahrenheit), but it is a target we are predicted to miss. The consequences could be dire: rising sea levels, water shortages, increased migration and the possibility of more frequent wars as we battle each other for resources.

It could turn out to be the greatest foe we have ever faced, and it is largely of our own making, yet there is still time to turn things around. Public awareness of the issue has never been higher and governments and individuals alike are slowly starting to wake up to their responsibilities - but will it all be too late? Part of the trouble is that the climate of a planet is an incredibly complex system with a lot of moving parts. Throughout its history Earth has warmed and cooled all on its own, alternating between ice ages and more temperate phases. How do we tease out our contribution from these background ups and downs? According to Dr Nicholas Attree, a research fellow at the University of Stirling, we could do a lot worse than to look at our neighbours. "What we see on Earth is natural climate cycles, plus human influence," he says. "Looking at the cycles of other planets means we can better understand our cycles and better understand our influence."

Attree has been looking closely at Mars' past climate. It is the most explored planet in the Solar System, with a host of active rovers trawling the surface and satellites whizzing around it examining the ground from on high. We have discovered that, like Earth, Mars cycles through periods with different climatic conditions. The reason is simple: gravity. Unlike Earth, Mars has no large Moon for stability. Combine that with the fact it is closer to the Solar System's big boys – Jupiter and Saturn – and it gets bullied by its giant neighbours. Being pulled this way and that leads to a change in Mars' obliquity – the tilt of the axis on which it rotates. It also changes the shape of Mars' orbit over time, making is successively more and less circular.

The upshot is that the intensity of sunlight falling on Mars is constantly changing, but in a regular way. A single cycle lasts tens of thousands of years. Attree has been looking at whether these climatic mood swings could have left a detectable signature on Mars today. "During warmer periods there would be an increased heat flow under the Martian surface," he says. "We've modelled how that heat would build up over time." In November last year he published a prediction that NASA's InSight may be able to detect that excess heat. InSight landed on the Red Planet in November 2018 and is equipped with a self-hammering 'mole'

Above: The thick clouds on Venus prevent us seeing the surface in visible light

Below: The HP³ probe on NASA's InSight mission is measuring Mars' internal heat

VENUS BY THE NUMBERS

464°C

Average temperature – about twice as hot as an oven

92

Atmospheric pressure compared to Earth – same as being one kilometre (0.62 miles) underwater

0.69

Venus' albedo – it reflects 69 per cent of sunlight

96.5%

of the Venusian atmosphere is carbon dioxide

243

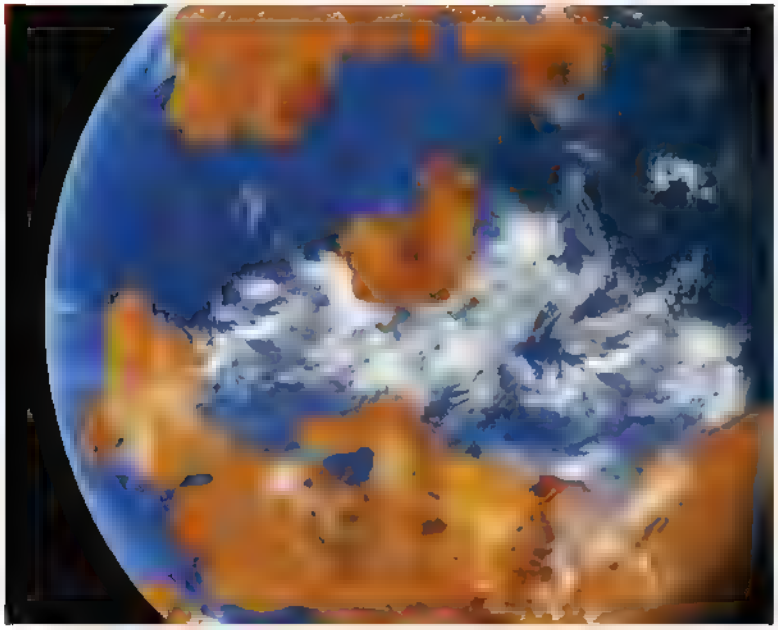
Days for Venus to rotate, leading to a static climate

60

Winds move 60-times faster than Venus spins

600 MILLION YEARS

Venus' age when runaway greenhouse effects began



Left: Some researchers argue that Venus would have been a potentially habitable planet long ago

designed to burrow into the Martian dirt. Among its instruments is a thermometer - the Heat Flow and Physical Properties Package, or HP³, perfect for looking at Mars' sub-surface heat.

Unfortunately the mission has been beset with difficulties. On its first attempt the mole reached a depth of just 35 centimetres (13.8 inches) before getting stuck. Mission scientists are still trying to puzzle out the problem and see if it can get as deep as planned, but by their own admission it isn't looking promising. Detecting Attree's predicted excess now looks difficult. "We were only likely to find it if the instrument was functioning perfectly," he says. All is not lost, however. There is another way to keep track of Mars' past climate cycles: carbon dioxide. Today the gas that's causing us so many woes on Earth is the main constituent of the Martian atmosphere. Yet the air is so thin that the atmospheric pressure on Mars is just 0.6 per cent of Earth's. Carbon dioxide is also frozen into

THE CHANGING CLIMATE OF VENUS

According to research, our neighbour's environment has changed dramatically

STEP 1

Magma ocean

Just like the primitive Earth, early Venus was still largely molten as a result of the high-energy impacts that formed the planet in the first place. This led to a widespread ocean of magma (molten rock) across the planet, leading to very high temperatures.

STEP 2

Gas and steam

Impacts added additional material to Venus, including a significant amount of water. Coupled with the heat from the magma ocean and Venus' proximity to the Sun, an early atmosphere began to form around the planet, largely made of carbon dioxide and steam.

STEP 3

Cooling and condensing

Over time the number of impacts began to die away; the unbattered planet began to cool down and a solid crust formed on the surface. Steam started to condense out of the atmosphere and fall as rain, creating Venusian lakes, rivers and seas.

STEP 4

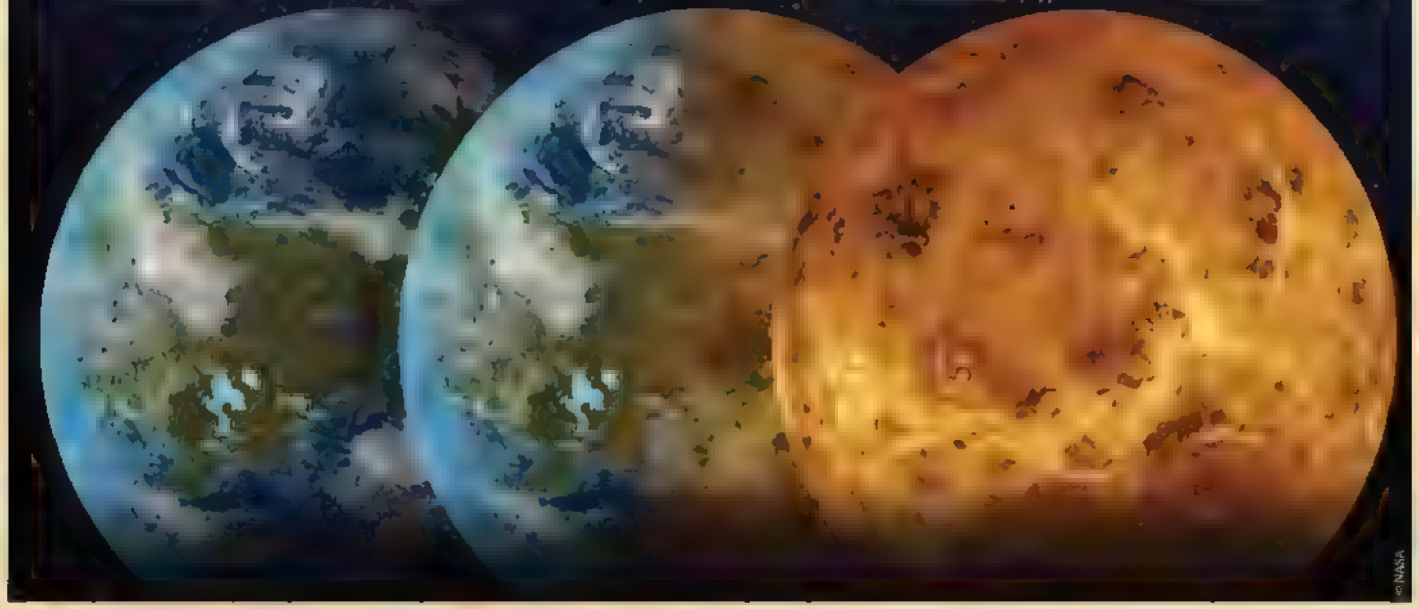
Vociferous volcanism

Deep inside the planet, under the crust, the magma ocean persisted. This led to wide-scale volcanism across Venus. Today we can still see these volcanoes, including the planet's tallest – Maat Mons. Eruptions added huge quantities of carbon dioxide back into the atmosphere.

STEP 5

Global warming

As we've discovered on Earth, carbon dioxide is a powerful greenhouse gas. It lets solar energy in, but makes it hard for it to escape. Over time this has raised the temperature on Venus, far beyond the boiling point of water. No lakes, rivers or seas remain.



the Martian ice caps. When changes to Mars' orbit and tilt increase the Sun's intensity, the carbon dioxide ice sublimates – turns straight from a solid to gas – and carbon dioxide is added to the Martian atmosphere. When things turn colder, the gas is deposited back onto the ice caps. In the 1960s it was predicted that the atmospheric pressure on Mars cycles in this way, getting as low as four times less than today's level and as high as double. Yet evidence to back this up has remained elusive. Then, in December 2019, a new study claimed to have found it at long last.

It all hinges on the layers of carbon dioxide dry ice and water ice on the planet's south pole. A kilometre (0.62 miles) deep, it contains as much carbon dioxide as currently exists in the entire atmosphere. Radar measurements from orbiting satellites suggest the cap is formed of alternating layers of dry and water ice. Dry ice trapped under water ice shouldn't be stable, yet it seems to persist. Modelling by Peter Buhler, a planetary scientist at NASA's Jet Propulsion Laboratory, is attempting to explain its longevity. Each time Mars warms up, some of the dry ice remains trapped under the water ice. The carbon dioxide that does escape is eventually deposited back on top of the water ice when temperatures plummet. That leads to the layering we see. Studying these layers should allow researchers to more accurately construct a picture of Mars' climate stretching back billions of years to a time when the planet may have been habitable. Ultimately we may get a better answer to the question of whether there's ever been life on Mars.

According to Michael Way from NASA's Goddard Institute for Space Studies, it could also help work out where to land when planning future human missions to the Red Planet. "They'd definitely want to talk to the climate modellers," he says. "It could tell you where to place your settlements or where the sub-surface water is most likely to be." Way and his colleagues have been adapting NASA's model of Earth's climate and applying it to other bodies in the Solar System, including Mars. It's known as a general circulation model. "It combines factors such as ocean circulation, wind circulation, cloud dynamics and different types of cloud," Way says. "It also estimates how many photons of light enter our atmosphere and are absorbed or reflected." Porting this model over to other worlds is not an easy task. "Applying it to modern Mars is very challenging," he says. It should get easier with the passage of time as improvements in computing power allow more intricate models to run in a shorter amount of time.

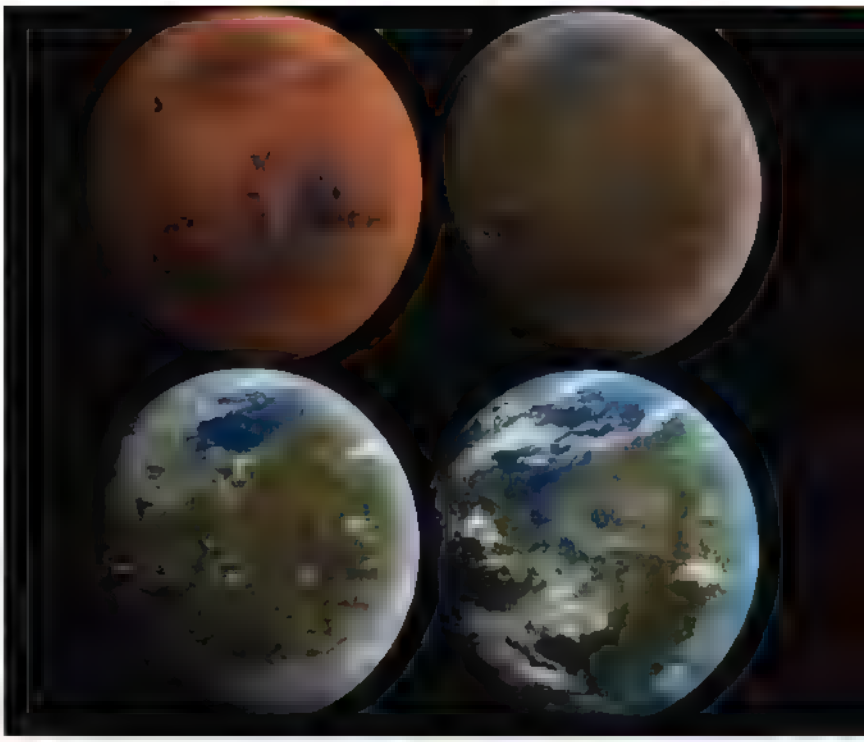
If Mars is hard, then modelling Venus' climate is even tougher. The world called Earth's 'twin' is an unforgiving hellhole. Thick clouds of carbon dioxide trap the Sun's heat, sending temperatures soaring beyond 400 degrees Celsius (752 degrees Fahrenheit). The atmospheric pressure is nearly one hundred times greater than Earth's and over 15,000-times higher than on Mars. That has severely restricted our ability to land space missions on Venus. Those that did make it to the surface succumbed very quickly to the mayhem. "We have very few data points for Venus," says Way. Unlike Mars you can't just run rovers around, taking lots of temperature measurements. "Our models struggle as a result," he says.

The models that have been devised so far point to two different possible climatic histories for Venus, depending on how long the planet's early magma ocean hung around. The rocky planets were formed when lumps of rock and metal called planetesimals smashed into one another with such ferocity that the solid materials melted. Being closer to the Sun, whose light was more intense at the time, combined with the presence of a hot magma ocean, created an atmosphere of steam and carbon dioxide. "The atmospheric pressure would have been one thousand times greater than the modern Earth," says Way. A molecule of water is H_2O - two atoms of hydrogen bonded to one atom of oxygen. On a hot Venus this bond would have been broken regularly. The hydrogen is lost to space and the oxygen becomes trapped inside the magma ocean. "If that's the case then Venus has been a dry, desiccated world for most of the last 4 billion years," says Way. The alternative is that the magma ocean was a much shorter lived phase. "Then it would have been cool enough to condense water into lakes, rivers and oceans," says Way. In other words, far more Earth-like than today. Perhaps the Solar System had two habitable planets at the same time.

If it's the latter then Venus has experienced a huge change in climate over the last 4 billion years, largely thanks to the role of carbon dioxide. Given our current climate predicament on

Right: One day it may be possible to engineer Mars' climate to be more hospitable

Below: The ESA's Huygens probe touched down on Saturn's largest moon Titan in 2005

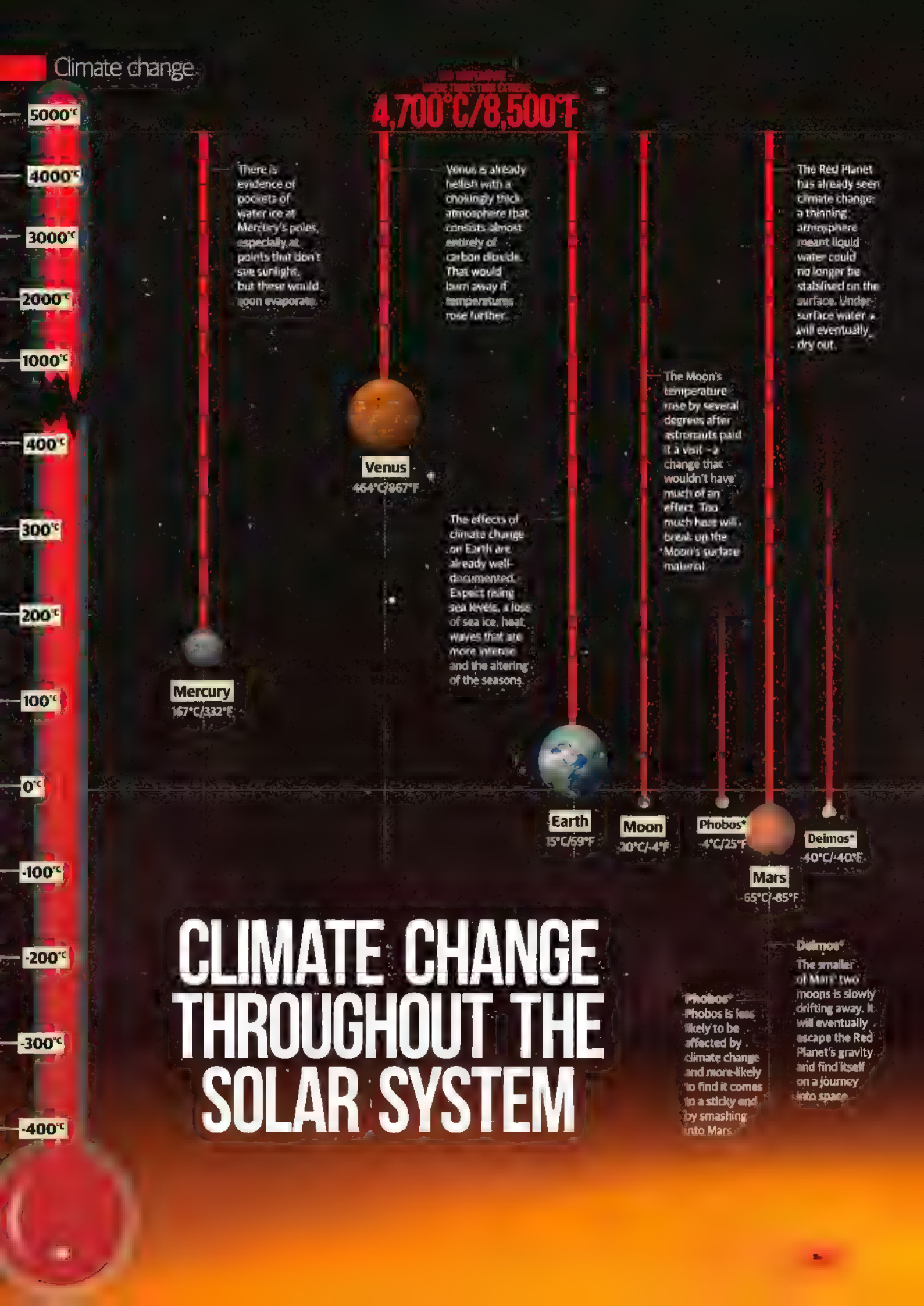


Source: Wikimedia © Dmitri Ballard

Source: Wikimedia/ESA/NASA

What killed the dinosaurs?

It's famously attributed to an asteroid impact, which threw huge volumes of debris into the sky and blocked out the Sun. A rapid change followed which put pressure on the big lizards.


Climate change
5000°C
4000°C
3000°C
2000°C
1000°C
400°C
300°C
200°C
100°C
0°C
-100°C
-200°C
-300°C
-400°C
4,700°C/8,500°F
There is evidence of pockets of water ice at Mercury's poles, especially at points that don't see sunlight, but these would soon evaporate.
Venus is already hellish with a cloyingly thick atmosphere that consists almost entirely of carbon dioxide. That would burn away if temperatures rose further.
The Red Planet has already seen climate change: a thinning atmosphere meant liquid water could no longer be stabilised on the surface. Underground water will eventually dry out.
The Moon's temperature rose by several degrees after astronauts paid it a visit – a change that wouldn't have much of an effect. Too much heat will break up the Moon's surface material.
Venus
464°C/867°F
The effects of climate change on Earth are already well-documented. Expect rising sea levels, a loss of sea ice, heat waves that are more intense and the altering of the seasons.
Mercury
167°C/332°F
Earth
15°C/59°F
Moon
-20°C/-4°F
Phobos*
-4°C/25°F
Deimos*
-40°C/-40°F
Mars
-65°C/-85°F
CLIMATE CHANGE THROUGHOUT THE SOLAR SYSTEM
Deimos*
The smaller of Mars' two moons is slowly drifting away. It will eventually escape the Red Planet's gravity and find itself on a journey into space.
Phobos*
Phobos is less likely to be affected by climate change and more likely to find it comes to a sticky end by smashing into Mars.

***Ganymede**
There is no atmosphere to trap heat on Ganymede, but it has its own magnetic field thanks to past heating that melted ice and caused rock to sink inwards.

*** Europa**
The surface temperature of Europa is largely determined by its ability to retain the Sun's heat. Ice on its surface would be lost if the moon was heated though.

We know that our Sun will become a red giant in approximately 5 billion years time. By then it will have consumed the terrestrial planets, though some planetary material will assimilate with this gas giant.

*** Titan**
As its atmosphere has warmed in the past, pockets of liquid nitrogen may have exploded from the moon's crust. It suggests Titan – which sees liquid methane fill those craters – may be susceptible to climate change.

*** Enceladus**
Since it is mainly covered by fresh, clean ice, Enceladus will undoubtedly suffer should temperatures rise.

In the case of the Sun becoming larger and warmer, the rings of Saturn would end up being vaporised since they are made almost entirely of water ice.

The impact of human industry

We've added carbon dioxide to the atmosphere, trapping more heat from the Sun. Our planet will adjust over time, but not soon enough to avoid severely impacting our way of life.

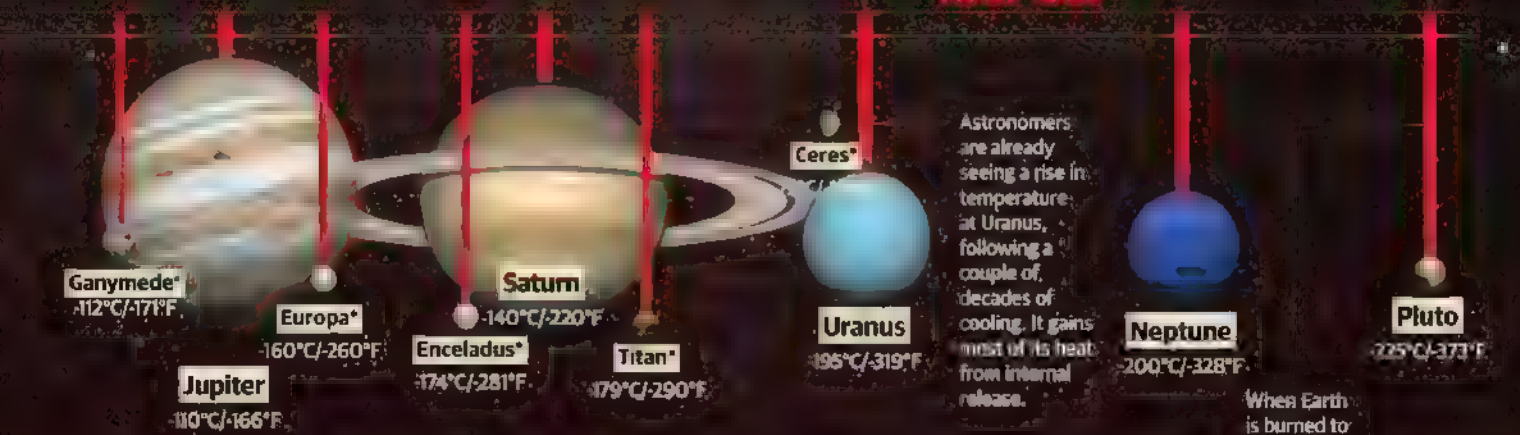
*** Ceres**
The dwarf planet Ceres is already talked of as potentially supporting life, and it is relatively warm and wet. Internal heat prevents it freezing up – a future home?

It's odd, but Neptune, despite being further away than Uranus, is actually warmer. Its atmosphere will boil off into space as it gets hotter.

15C/59F

Astronomers are already seeing a rise in temperature at Uranus, following a couple of decades of cooling. It gains most of its heat from internal release.

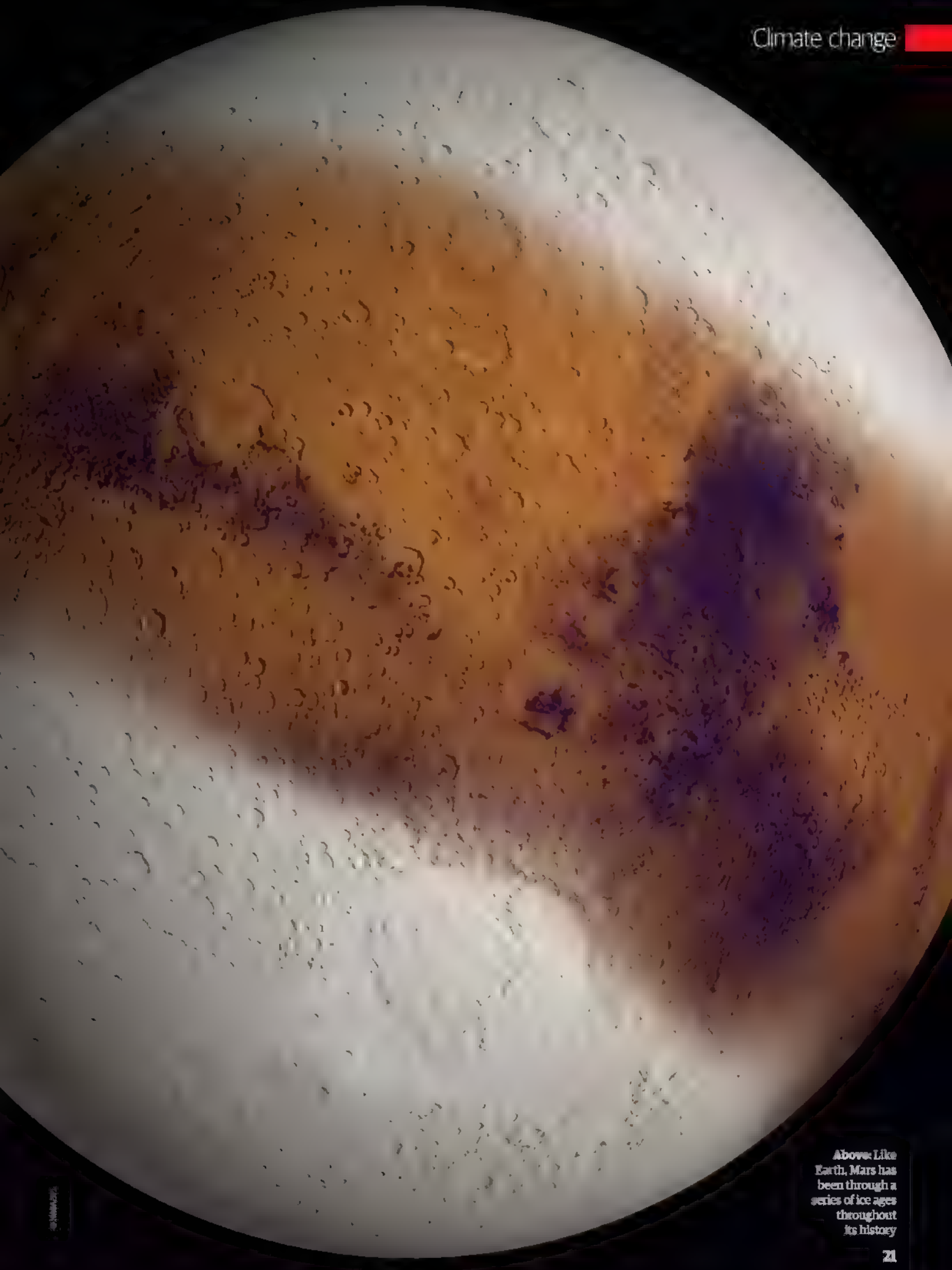
When Earth is burned to a crisp, Pluto will end up being in an odd situation of having average temperatures that mirror our own today. It will have a liquid water surface and a thick [illegible]



Earth, is there anything we can learn from our neighbour? "It's a compelling idea," says Way, "but it is a difficult comparison to make." The driver of Venusian climate change is largely thought to have been large-scale volcanism dumping huge quantities of carbon dioxide into the atmosphere far more than we've added to the Earth's since the Industrial Revolution. "Unlike Venus, the Earth will eventually adjust to this increase in carbon. We just may not be around to see it," Way says.

Along with Venus and Mars, Way and his colleagues have also secured funding to model the climate of Titan – Saturn's largest satellite and the only moon in the Solar System with a thick atmosphere. "Titan is interesting as the density of its atmosphere is only 1.5 times Earth's," Way says. "A lot of its climate dynamics are similar too." Part of the attraction of studying Titan is the wealth of data that came back from the Cassini mission and the Huygens lander that touched down on the satellite in 2005. "What it found shocked a lot of us – it blew people's minds," says Way. Like Earth, there is liquid on the surface, which evaporates and condenses as rain. Yet instead of water it is methane, possibly because of the moon's very cold temperature. Researchers have also spotted complex chemicals known to be the building blocks of life. Understanding Titan's climate today could tell us whether it has ever had suitable conditions in the past for this chemistry to jump from prebiotic chains of molecules to full-blown biological organisms. Dragonfly could be a potential game changer in this effort. In the summer of 2019, NASA announced that it had approved the audacious rotorcraft lander that would take off and land in several sites across the Saturnian satellite, much like its insect namesake. It is due for launch in 2026 and will arrive in 2034. According to Way, climate modellers are "eagerly awaiting its arrival."

All these efforts to understand the climates of the worlds we share the Solar System with will do more than just inform our own battle against climate change. They will also give us a better idea of what exactly makes a planet habitable in the long term. That is sorely needed in the search for life beyond the Solar System. If Venus was a pleasant planet before volcanism ran rampant, then perhaps we shouldn't rule out planets in similar positions to Venus around other stars. Maybe there is too much focus on the idea of a habitable zone – the narrow region around a star where the temperature is right for liquid water. The contents of a planet's atmosphere has a huge role to play in distributing heat, and surely needs to be taken into account when assessing a world's suitability for life. Who knows, one day we may have to evacuate this beautiful planet of ours. If so, knowing which worlds around the Sun and beyond could be new potential homes could prove vital to the continuation of our species.



Above: Like Earth, Mars has been through a series of ice ages throughout its history

PLANET NINE CONTROVERSY

THE SOLAR SYSTEM'S BLACK HOLE

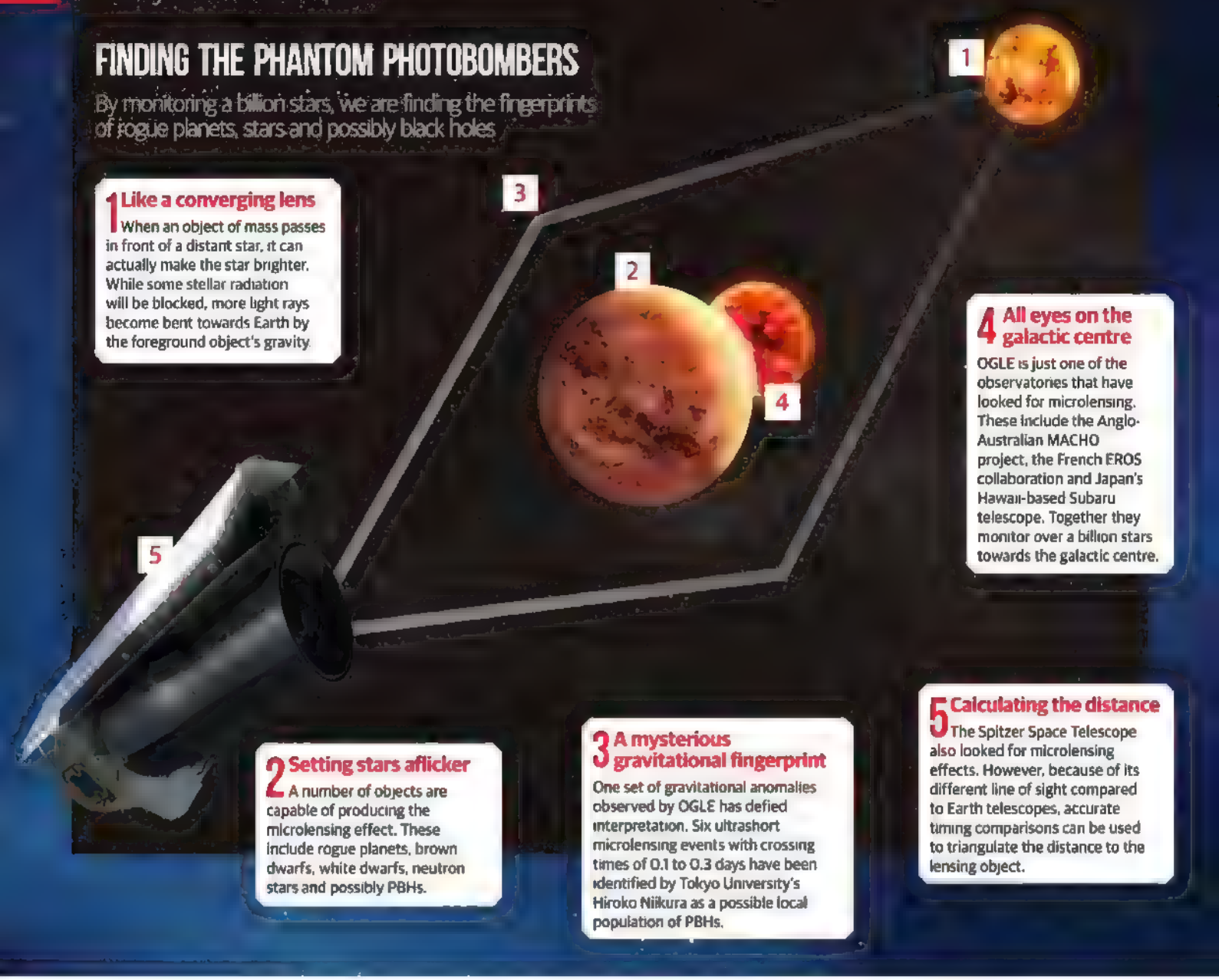
Reported by James Romero

As the hunt for a mysterious world at our solar neighbourhood's edge steps up, something more exotic might also fit the bill

It's been four years since Mike Brown, the astronomer who removed Pluto's status as a planet, added a hypothetical one back in to explain strange orbits in the outer Solar System. In another two years the Vera C. Rubin Observatory will map those celestial backwaters to help find Brown's Planet Nine. But what if this target can't be seen? It's a possibility that hit the headlines last year when Planet Nine was replaced, at least in excited media headlines, by an ancient black hole. Brown himself addressed the possibility, writing on Twitter: "P9 could definitely be a black hole, as long as it is the right mass. In fact, it could also be a six-Earth-mass hamburger." So is a black hole lurking in the outer Solar System a statistical possibility worth considering? Or a whopper of a stab in the dark?

FINDING THE PHANTOM PHOTOBOMBERS

By monitoring a billion stars, we are finding the fingerprints of rogue planets, stars and possibly black holes



1 Like a converging lens
When an object of mass passes in front of a distant star, it can actually make the star brighter. While some stellar radiation will be blocked, more light rays become bent towards Earth by the foreground object's gravity.

2 Setting stars aflicker
A number of objects are capable of producing the microlensing effect. These include rogue planets, brown dwarfs, white dwarfs, neutron stars and possibly PBHs.

3 A mysterious gravitational fingerprint
One set of gravitational anomalies observed by OGLE has defied interpretation. Six ultrashort microlensing events with crossing times of 0.1 to 0.3 days have been identified by Tokyo University's Hiroko Niikura as a possible local population of PBHs.

4 All eyes on the galactic centre
OGLE is just one of the observatories that have looked for microlensing. These include the Anglo-Australian MACHO project, the French EROS collaboration and Japan's Hawaii-based Subaru telescope. Together they monitor over a billion stars towards the galactic centre.

5 Calculating the distance
The Spitzer Space Telescope also looked for microlensing effects. However, because of its different line of sight compared to Earth telescopes, accurate timing comparisons can be used to triangulate the distance to the lensing object.

Answers are out there among trans-Neptunian objects (TNOs). Ancient debris left over from planet formation, the TNOs were swept up by a young, migrating Neptune and dumped far from the Sun in the Kuiper Belt. The ice giant's hold on this ring of rubble continues today, though its influence has changed. Once the source of gravitational chaos, Neptune now brings order to the Kuiper Belt. Any resident knocked out of the orbital plane is brought into line. "TNOs are really interesting because they explore the outer reaches of the Solar System but they're partially driven by Neptune, which gives them a little kick," says Jakub Scholtz of Durham University. "These kicks randomise them in such a way that they should look pretty uniform."

It was the lack of uniformity that made Brown and his California Institute of Technology (Caltech) colleague Konstantin Batygin's discovery so intriguing. Six TNOs with similarly tilted orbits were all found pointing in a similar direction. Worldwide headlines followed when the culprit was identified as a five to ten Earth-mass planet. The theory raised questions, primarily about what a large planet was doing out there. Observations of other planetary systems have shown building materials that far out in short supply, ruling out in-situ formation. Was Planet Nine another reject from the inner Solar System or a captured interstellar wanderer?

Scholtz doubts the ejected planet scenario, however, as a single gravitational kick simply elongates a planet's orbit. Its closest approach would still stay roughly the same unless you can account for a series of kicks, which is significantly less likely. The other major question was more obvious. If Planet Nine was a victim of cosmic piracy, where is the stolen bounty?

This was always going to be a challenging hunt. Planet Nine is thought to be several times the size of Earth due to the observed influence, but it's way out there, at least ten-times further than Neptune. Leading the search in recent years has been the Dark Energy Survey, which maps the Kuiper Belt looking for unexplained gravitational influence. Meanwhile NASA's Backyard Worlds project posts images from the Wide-field Infrared Survey Explorer (WISE) for the public to search themselves.

Neither have found their prime target, which is why many hopes are pinned on the Vera C. Rubin Observatory. Coming online in 2021, it aims to characterise around 40,000 TNOs and scattered disc objects. "If Planet Nine is a conventional planet,

I think it is expected to be discovered by the Vera Rubin Observatory," says Ed Witten, a theoretical physicist at the Institute for Advanced Study.

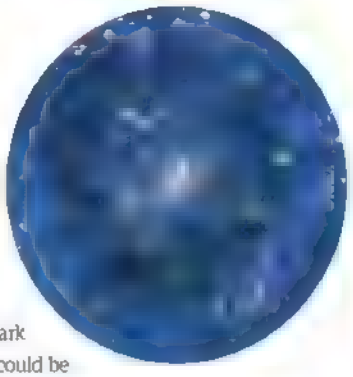
But perhaps Planet Nine isn't a planet at all. As Brown acknowledged, all we know about it is its influence on TNOs. Everything else is inferred. And while there was no reason to doubt Brown and Batygin's original suspect, a challenger emerged when Scholtz and James Unwin, assistant professor at the University of Illinois at Chicago, came across something interesting in the Chilean Andes. There the Optical Gravitational Lensing Experiment (OGLE) monitors a billion stars towards the galactic centre, looking for shadowy brown dwarfs and free-floating planets passing across the starfield.

The resulting gravitational 'microlensing' events give clues about their mysterious photobombers. However, one microlensing signature proved difficult to attribute. Ultrashort occultation events lasting just a few hours kept appearing. The OGLE team's conclusion was a local population of free-floating planets. But six nearby rogue worlds seemed a lot given the average number of planets produced per star across the galaxy.

In January last year Tokyo University's Hiroko Niikura proposed a radically different culprit: a community of nearby primordial black holes (PBHs). These were proposed by Stephen Hawking in the 1970s as a product of the early universe, when all matter was packed together. This meant random patches of slightly elevated density could frequently reach a critical level that trapped them behind gravitational points of no return. The result was huge numbers of low-mass black holes.

For a few decades PBHs were best known as a potential explanation for dark matter. Mostly because you didn't need to conjure up new particles, and cosmologist's models could produce

> "PLANET NINE COULD DEFINITELY BE A BLACK HOLE, AS LONG AS IT IS THE RIGHT MASS" MIKE BROWN



universes full of them. However in recent decades OGLE and other microlensing surveys have dashed those hopes by drawing blanks for many critical proposed PBH masses. "There's still some window," says Kathryn Zurek, a dark matter theorist at Caltech. "They could be 10 per cent or 20 per cent of dark matter, but you're not driven to them as a candidate in comparison to 20 or 30 years ago."

While the dark matter mystery remains, Niikura's paper claimed a local PBH population of 0.5 to 20 Earth masses could reproduce OGLE's six ultrashort microlensing events. For Scholtz and Unwin, that familiar mass range immediately caught the eye. "As physicists we're trained to think there are no coincidences," says Scholtz, who wondered if one of Niikura's black holes was lured into the Solar System to warp TNO orbits. It's an intriguing scenario, not least because it replaces our ninth world with something far smaller.

To investigate their idea, Scholtz and Unwin compared capture probabilities for rogue planets and pocket black holes. In a paper posted last September they took a number for rogue planets

Above: For decades PBHs were best known as a potential explanation for dark matter

Below: The OGLE observatory looks for the fingerprints of free-floating planets passing across the starfield

© NASA

RESIDENTS OF THE OUTER SOLAR SYSTEM

What else lies in this cold region of space?

Pluto

Perhaps the most famous resident of the Belt, Pluto is the largest and most massive member. It is also the most studied, thanks to the New Horizons probe.

© NASA

Sedna

Sedna has an extreme orbit that ranges from 76 AU to over 900. While Planet Nine doesn't explain Sedna's orbit, it could provide the buffer that kept it from being ejected.

© NASA/JPL-Caltech

Haumea

Though not directly observed, Haumea is thought to be an ellipsoid world. In October 2017 astronomers announced the discovery of a ring system, the first around a trans-Neptunian object.

© José Antonio Peñas/SINC

Eris

About the same size as Pluto, this dwarf planet and its small moon Dysnomia orbit three-times farther from the Sun. Its high eccentricity orbit means it was likely scattered by Neptune.

© ESO

2012 VP_{113}

A minor planet with the farthest closest approach to the Sun in the Solar System, this extreme TNO's orbit was interpreted as evidence of Planet Nine.

© NASA/JPL-Caltech

Makemake

Orbiting at a highly inclined 29 degrees to the plane of the Solar System, Makemake's orbit lies far enough from Neptune to remain stable and free from perturbation from the ice giant.

© ESO

Source: Wikipedia Commons © Jason Davis The Planetary Society

Right: Proposals to reach Planet Nine are based on lightsail technology

Below: The Kuiper Belt is made up of scattered debris left over from planetary formation

passing through our Solar System based on planet production and ejection per star, and one for the population of PBHs predicted by OGLE. They applied these to a 2017 model from Nadav Goulinski at the Israel Institute of Technology which allows you to throw bodies of various mass and velocity at our Solar System to see what sticks.

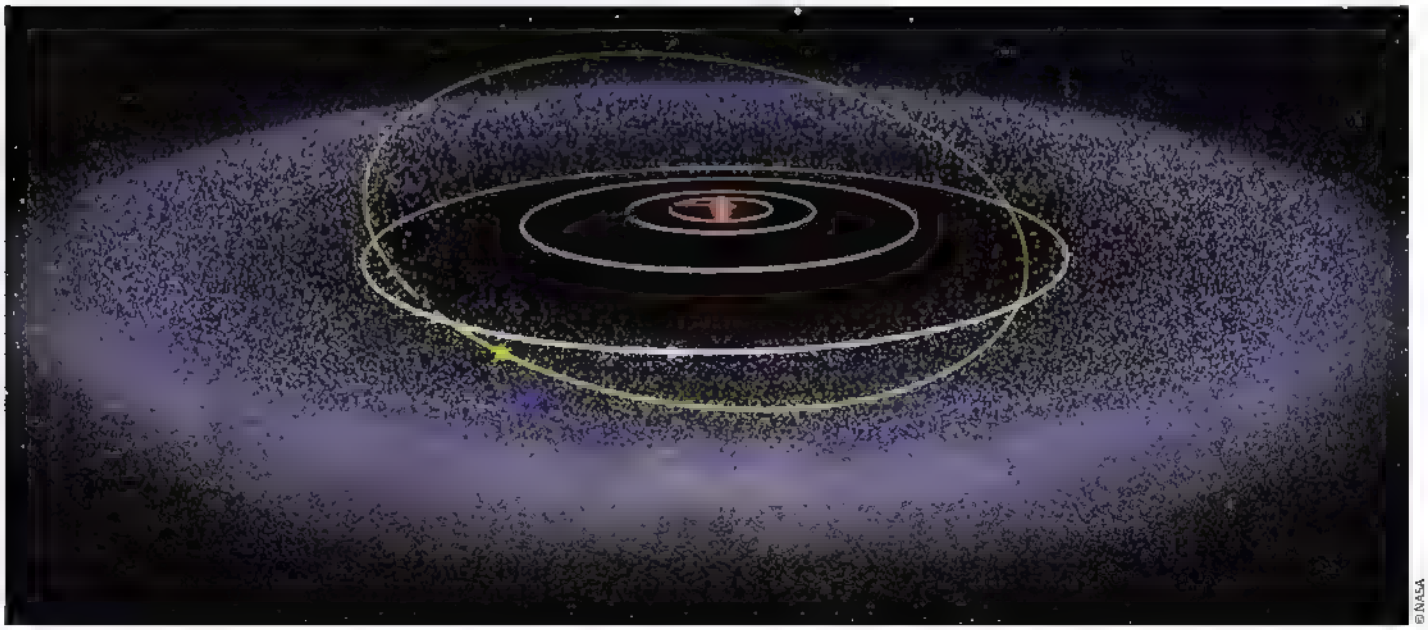
Goulinski's model highlighted two points: rogue planet capture is rare, but black hole capture is rarer still. While the model suggests a quarter of a kilometre per second as a top-end velocity for capture, rogue planets travel at the velocity of their parent stars, at around 40 kilometres (24.9 miles) per second. PBHs are thought to move at the velocity of cold, collisionless dark matter: expected to be several times faster again. But cosmic piracy is a numbers game, and while rogue planets are more speed matched to our Solar System, their lower frequency seems to even things up.

"I don't want to use the word miraculous, but surprisingly it almost cancels out," says Scholtz. "If you were willing to think about Planet Nine as a captured rogue planet, then given the OGLE result you should consider thinking about it as a captured black hole." Not everyone agrees. Zeeve Rogozinski is a planetary dynamics researcher at the University of Maryland. He questions Scholtz's dismissal of planetary ejection to account for Planet Nine's distant location, pointing to Solar System evolution models that work better with an extra primordial ice giant. The 'five-planet Nice model' includes the premise that Uranus and Neptune formed in between Jupiter and Saturn before ejection. "If you add a fifth ice giant to that scenario, it's much more likely that Uranus and Neptune would remain in our Solar System," says Rogozinski.

If Scholtz is right and capture is most likely, then the PBH hypothesis would clearly benefit from proof these objects exist in abundance. Nikura suggests comparing microlensing events observed towards the galactic centre – where both rogue planets and PBHs are thought to be prevalent – with data from the Large Magellanic Cloud. This local satellite galaxy is relatively depleted in planets, so the contribution from PBHs could be teased out.

Building this theoretical case seems sensible. And yet, with a potential black hole inside our Solar System, it is not surprising Scholtz's paper inspired a host of mission concepts aiming straight for this mysterious gravitational heavyweight. "It seems obvious that if there is a black hole in the outer Solar System, we want to find it," says Witten. He was first off the mark with a concept for laser-propelled, lightweight spacecraft attached to lightsails. Based on the Breakthrough Starshot concept to reach our nearest star Alpha Centauri, Witten suggested launching hundreds of craft spreading out along our Solar System's orbital plane. Unlike the Starshot craft, Witten's would carry an atomic clock and a transmitter. This additional weight would mean a decade-long journey but would allow each craft to alert us if they encounter a planet or black hole through their acceleration.

Others proposed improvements to Witten's proposal. In his own paper Rogozinski scrapped the weighty clock and suggested looking for bends in a craft's trajectory from the same gravitational influence. Harvard theoretical physicist Avi Loeb thought both approaches failed to address the noisy environment inside which our target likely resides. "Once you go past about a hundred AU you're battered by the interstellar medium," explains Scholtz. "For a precision mission this could be a serious hurdle."



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A BREAKTHROUGH IN REACHING THE OUTER SOLAR SYSTEM

How a mission to Alpha Centauri has inspired an approach to pinpoint our mysterious outer Solar System object

1 Light beam transportation

In the 1960s it was suggested the newly invented laser could accelerate armies of ultralight sail-bound craft a substantial fraction of the speed of light, opening up interstellar travel – or a fast way to reach the outer Solar System.

3 A perfect mirror

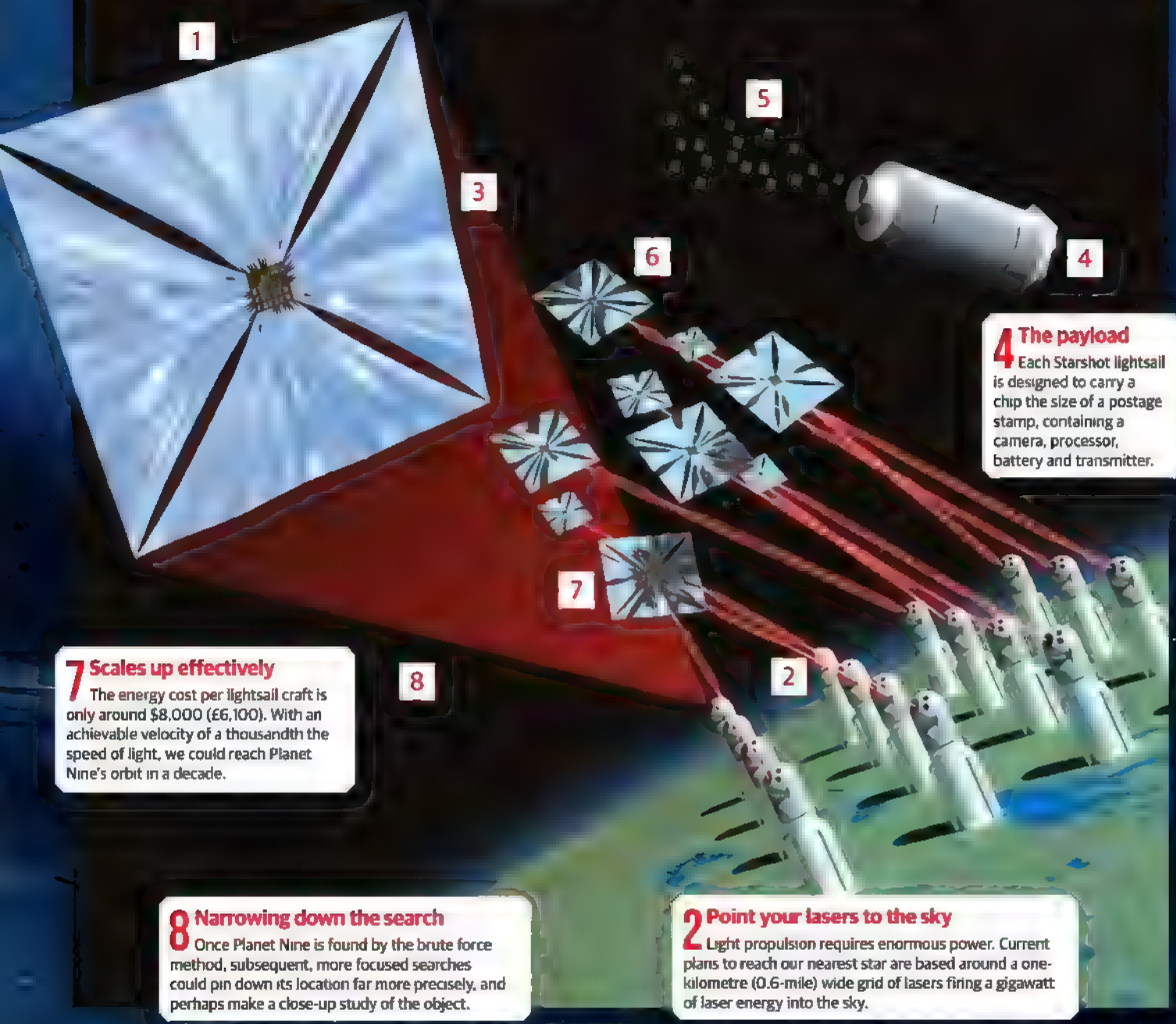
Each proposed lightsail is four metres (13 feet) across, but just a few hundred atoms thick. The sail material needs to be an almost-perfect mirror, reflecting 99.99 per cent of the photons that reach it, otherwise the lasers will burn it up.

5 Hedging your bets

With no clues where around its proposed orbit Planet Nine or our black hole might be, Starshot's safety in numbers approach to space travel would see hundreds of spacecraft launched in various directions.

6 Sensor network

In Ed Witten's Starshot-inspired proposal to find Planet Nine, each craft is fitted with an atomic clock, broadcasting time signatures. Any craft on the right path will accelerate due to our target's gravity, lengthening the gaps between signals received on Earth.



4 The payload

Each Starshot lightsail is designed to carry a chip the size of a postage stamp, containing a camera, processor, battery and transmitter.

7 Scales up effectively

The energy cost per lightsail craft is only around $8,000 (£6,100). With an achievable velocity of a thousandth the speed of light, we could reach Planet Nine's orbit in a decade.

8 Narrowing down the search

Once Planet Nine is found by the brute force method, subsequent, more focused searches could pin down its location far more precisely, and perhaps make a close-up study of the object.

2 Point your lasers to the sky

Light propulsion requires enormous power. Current plans to reach our nearest star are based around a one-kilometre (0.6-mile) wide grid of lasers firing a gigawatt of laser energy into the sky.

THE VERA C. RUBIN OBSERVATORY: HOW IT WILL HELP FIND PLANET NINE

In 2021 the Vera C. Rubin Observatory will come online, spending ten years searching the entire southern sky for objects of all types beyond Neptune

Left: The Vera C. Rubin observatory will map the outer Solar System with the world's largest digital camera

1 Mirror in motion
The observatory's 8.4-metre (27.5-foot) mirror can track across to survey the entire Southern Hemisphere sky twice a week. This will come in handy for locating Planet Nine or our mystery black hole.

2 A camera the size of a car
Images will be recorded by a 3 2-gigapixel camera, the largest ever constructed. It will take a 15-second exposure every 20 seconds to help detect and map 40,000 objects beyond Neptune.

3 Onsite maintenance
To maximise imaging time for characterising 100-times more TNOs than are currently known, the observatory has a cleaning and coating area where mirrors are washed and recoated.

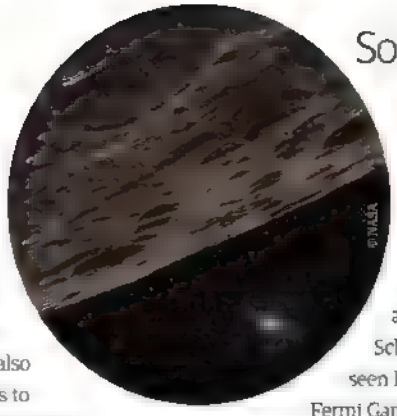
4 Keeping the mirror cool

The telescope's sensitivity is maintained by cooling the mirror temperature This could allow for the detection of flares given out if our primordial black hole consumes a passing comet.

5 At home in its environment

The observatory's orientation was selected after extensive testing to minimise air disturbance, giving some confidence that it will be able to detect brightness variations, measure TNO colour and infer composition

© KSTP Project



Loeb proposed a longer mission sending craft weighing a kilogram or more to minimise drag This added weight could also allow for instruments to differentiate between a planet and a black hole However, if such a multi-decade trip doesn't appeal, a laser-shot mission will be limited to locating our elusive gravity source Then Earth telescopes can at least focus down on a particular patch of sky where a distant planet might be teased out eclipsing background stars. "If it's a black hole the size of a baseball, we wouldn't be able to observe any occultations," points out Rogoszinski.

In the meantime, Scholtz highlights a potential signal that could tip the planet-black hole scales towards the latter. While primordial black holes disappointed as dark matter we'd still expect one to be surrounded by the mysterious substance

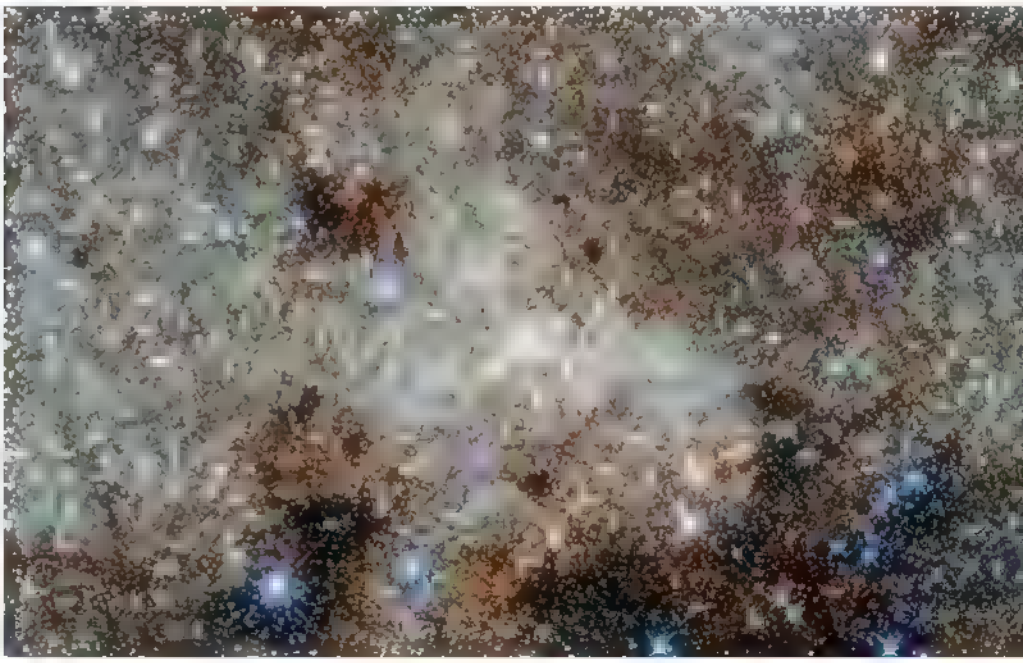
Indeed, Scholtz calculated his PBH would have a five-centimetre (1.9-inch) radius and come with a dark matter halo extending out a billion kilometres. "In most scenarios dark matter can annihilate and form visible signals," says Scholtz, who suggests it's possible we've seen halo signals within observations of the Fermi Gamma-ray Space Telescope Though he admits it's one thing collecting this data it's another teasing it out from its billion-photon database

Unfortunately, whether it's dark matter annihilations, starfield occultations or spacecraft gravitational deflections, this mystery in the outer Solar System isn't giving up its secrets easily In the absence of anything firmer, Scholtz sees the positives in the fact his theory can simultaneously explain two anomalies. Others need convincing.

"The odds are it's probably not a black hole," says Rogoszinski, who sees many reasons why this object has eluded observation without it being a tiny black hole. "Maybe its reflectance is very low or maybe there are no stars behind it to occult?" However he admits that if searches continue to draw blanks, at some point the probability will begin to shift. Zurek is in agreement. "I think it's probably not [a black hole], but it's not really ruled out If there's an existing instrument, let's have fun."

Fun is one way to describe such a discovery Scholtz goes with 'staggering' and a few other effusive terms. "To be able to experiment with the black hole, that would be a dream come true We could really understand a lot about gravity about general relativity but also about quantum mechanics It would be a new window into science"

> "IF PLANET NINE IS A CONVENTIONAL PLANET, I THINK IT IS EXPECTED TO BE DISCOVERED BY THE VERA RUBIN OBSERVATORY" BE W TEN



Above: Eccentric Kuiper Belt orbits are often influenced by both the inner and outer Solar System

Right: The OGLE facility may have spotted the fingerprints of primordial black holes within its starfield

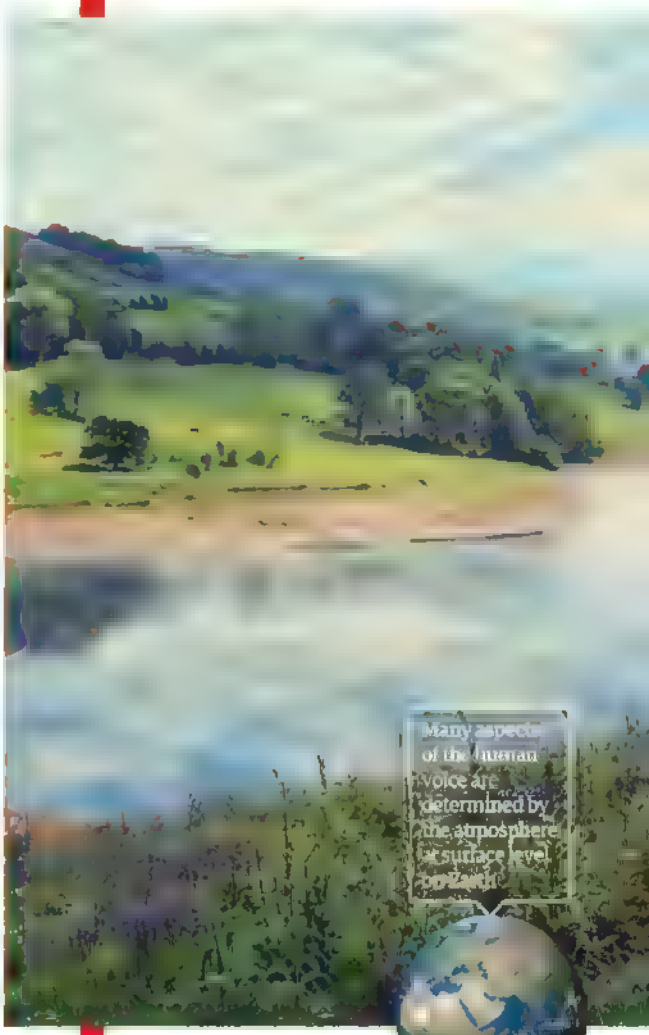
WHAT WOULD YOU SOUND LIKE ON OTHER WORLDS?

ALL ABOUT SPACE REVEALS HOW THE HUMAN VOICE WOULD DIFFER IF ASTRONAUTS WERE ABLE TO TALK ON OTHER WORLDS

Written by Lee Cavendish

Testing your vocal cords on another planet is a deadly experiment. If you were to voyage to another planet, step out of your spaceship and remove your helmet in order to announce your arrival, you'd be dead within minutes... or even seconds. However, if you were able to speak on other planets and moons throughout the Solar System, the varied atmospheres and surface conditions would affect your vocal cords in a different way than on Earth, making you sound like a different person.

Your ability to speak is possible because of airflow vibrating against the larynx, producing sound waves that then propagate through the atmosphere, which are then carried to, and received by, the eardrums. But what happens if the atmosphere, the medium for voice vibrations, and the surface conditions are tweaked somewhat?



EARTH

On Earth we are currently in a settled state of verbal communication. Earth sits in the Goldilocks Zone of habitability, where the planet is not too far away from the Sun. It's here where the temperature is just right, where the atmosphere evolved in such a way that made our planet an ideal spot for life to thrive.

As an evolutionary consequence, our voices have adapted to this friendly atmosphere that consists mostly of nitrogen. These atoms are relatively heavy and make up roughly 78 per cent of the atmosphere. Oxygen is the second most abundant, comprising 20 per cent, and the rest is made up of small amounts of argon, carbon dioxide and other gases.

Carbon dioxide is much more prevalent in the atmospheres of our neighbouring planets, and thus alone makes a huge change to the way our voices would sound. With it only in a small abundance on Earth it does not absorb as many vibrations, thus allowing screams and shouts to carry much farther.

VENUS

If this thought experiment became a reality, an astronaut would have to endure landing on a surface with pressures similar to swimming 900 metres (3,000 feet) below Earth's surface level. Not only that but Venus has the most intense temperatures of any planet in the Solar System. The average temperature is about 465 degrees Celsius (869 degrees Fahrenheit), which is hot enough to melt lead. The atmosphere of Venus is almost entirely carbon dioxide, with the percentage being a substantial 96 per cent.

The higher density of the air would cause your vocal cords to vibrate slower, meaning the pitch would be lower by half an octave. Simultaneously, the thick smog would cause the sound to travel faster, as the atmosphere acts more like a liquid than a gas. This would cause the frequency to be higher, so sounds would be squeakier as a consequence. Along with the fact that the predominantly carbon-dioxide atmosphere would absorb the waves, stifling them, your voice on Venus would sound as if you're doing a Donald Duck impression from far away.

© ESA

Similarities between Venus, Earth and Mars

all have iron-nickel c
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MARS

After being stripped away over billions of years, Mars has a very thin atmosphere. Similarly to Venus, it is almost entirely made up of carbon dioxide, with a similar percentage. However, unlike "Earth's evil twin", the atmosphere of Mars has a surface pressure equivalent to one per cent of Earth's at sea level and experiences an average freezing temperature of minus 63 degrees Celsius (minus 81 degrees Fahrenheit).

The carbon dioxide would once again absorb the vibrations, making your voice sound quieter. In fact, a speaker blaring out your favourite song would be barely audible if placed nine metres (30 feet) away. The other major difference on Mars is that the cold would lower the pitch of your voice, adding a huskier tone to it.

the thinnest atmosphere of all the
difficult to send
very far

TITAN

It's not a planet, but Saturn's moon Titan is arguably the most similar world to Earth in the Solar System. It is the only moon in [illegible] to have a dense atmosphere, which is 95 per cent nitrogen, and even experiments [illegible] similar to Earth's.

At the surface the air pressure is comparable to someone swimming roughly 15 metres (50 feet) deep in the ocean on Earth, combined with the moon's chilly temperatures. As Titan is nine times farther away from the Sun than Earth, it receives a fraction of the sunlight, [illegible] an average surface temperature of minus 179 degrees Celsius (minus 290 degrees Fahrenheit).

The similarity in atmospheric composition between Titan and Earth will give a recognisable tone to your voice, but with two main differences. The higher air pressure will cause the vibrations to travel slower and give slightly more bass to your voice. Secondly, as Titan's atmosphere is more abundant in nitrogen, the sound waves would be carried further, meaning that your voice would also appear louder to the receiver. This means that you [illegible] you're about to take a dip in the ocean of liquid methane.

Artists' impressions of Titan paint a picture of a gloomy world. Titan's atmosphere presents a thick orange haze that makes the moon difficult to observe.

The tantalising prospect of Titan

[illegible]

Exploration

Discover how humankind is blasting off into space

16 30 years of Hubble
Celebrating three decades of [illegible]

18 Rise of the Space Force
Signed into law in 2019, [illegible]

24 Secret missions
[illegible]

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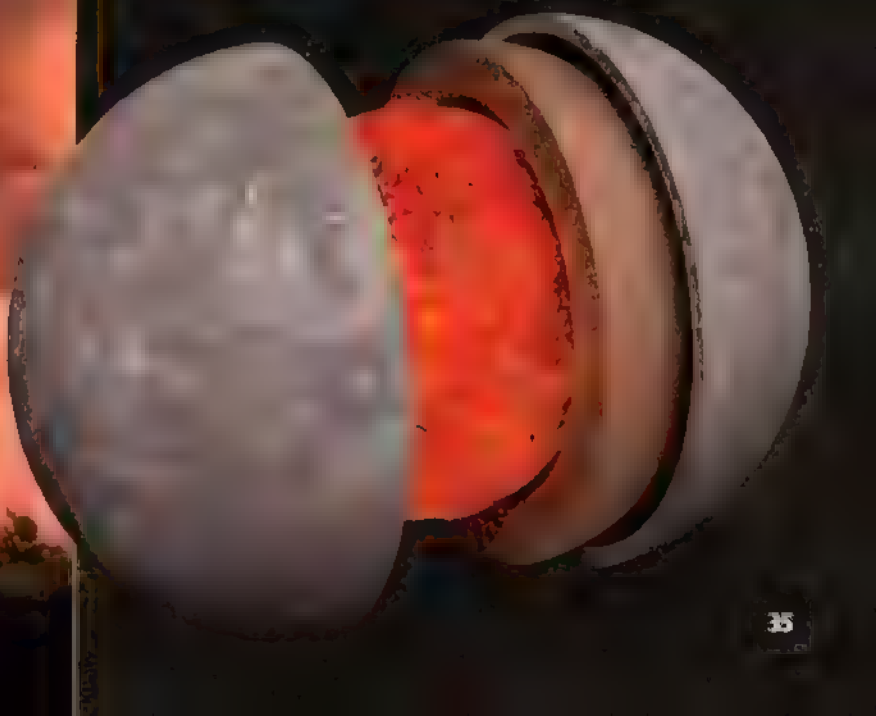
"This coming decade will be the golden age of Solar and heliophysics research"



30 YEARS OF HUBBLE

Celebrating three decades of an icon of science – and a triumph of technology

Reported by Andrew May

It's 30 years since NASA launched the Hubble Space Telescope into orbit on 24 April 1990. It was carried aloft in the payload bay of Space Shuttle Discovery, and for three decades Hubble's history was closely intertwined with the Shuttle's. It was originally scheduled for launch in 1986, but the tragic Challenger accident at the start of that year led to a four-year delay.

When Hubble finally made it into orbit, it still wasn't plain sailing. Almost immediately a serious flaw was discovered in the telescope's mirror which made stars look slightly blurred rather than sharp pinpoints of light. Since the whole point of putting Hubble above the Earth's atmosphere was to avoid the blurring that ground-based telescopes suffer from, this was disastrously bad news. For any other astronomical satellite the situation would have been terminal, but not Hubble. It was designed all along to be serviceable in space – another way its destiny was inextricably tied to the Shuttle.

Left: The Hubble Space Telescope was named after American astronomer Edwin Hubble

The first servicing flight, by Space Shuttle Endeavour in December 1993, was originally planned as a routine maintenance visit. Now it was an urgent rescue mission. In a series of tense spacewalks the astronauts replaced Hubble's main camera with a redesigned one and installed a corrective optics package for the other instruments. In what may be the second greatest feat of human spaceflight after the Moon landings, Hubble was brought back up to its design spec. Now it could see all the wonders of the universe with a clarity that could never be achieved down on Earth's surface. Four subsequent servicing missions, the last by Space Shuttle Atlantis in May 2009, have ensured Hubble remains the world's most powerful telescope to this day.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WHAT THE SCIENCE TEAM LOVE ABOUT HUBBLE

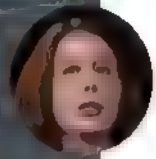
"HUBBLE IS A TIME MACHINE THAT'S LET US EXPLORE BACK OVER 13 BILLION YEARS OF TIME ... JUST TO ABOUT 400 MILLION YEARS AFTER THE BIG BANG"

Garth Illingworth, former deputy director of the Space Telescope Science Institute

Above: To most telescopes a globular cluster's core is just a blur of light, but Hubble sees individual stars

© NASA/ESA

"HUBBLE IS THE FIRST FACILITY THAT HAS GIVEN US THIS UNIQUE VIEW INTO THE ATMOSPHERES OF PLANETS BEYOND OUR SOLAR SYSTEM"



Nikole Lewis, co-leader of Hubble exoplanet studies

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"IT HAS REALLY CHANGED OUR UNDERSTANDING OF HOW DYNAMIC OUR SOLAR SYSTEM TRULY IS"

Heidi Hammel, planetary astronomer who has worked on Hubble since the 1990s

© NASA

As dark as the night sky looks from ground level, it never gets completely black due to airglow in the atmosphere, which limits the ability of earthbound astronomers to take long-exposure photographs. At Hubble's high altitude, however, the background sky really is pitch black, which means it can see incredibly faint objects if it stares at the same patch of sky for long enough. That's the rationale behind one of Hubble's most impressive achievements: the 'deep-field' images, of which the first was released in 1996 and the most recent – the Hubble Extreme Deep Field (HXDF) – in 2012. **All About Space** speaks to one of the scientists behind the project, Garth Illingworth.

"Before Hubble, we knew essentially nothing about galaxies in the first half of the life of the universe," he tells us. "That's the first 7 billion years of the universe's 13.8-billion-year life. Now Hubble, through remarkable surveys like HXDF, has probed into the era of the first galaxies." As a specific example Illingworth cites GN-z11, the most distant galaxy discovered by Hubble. "Just 400 million years after the Big Bang, Hubble is looking back through 97 per cent of all time to see GN-z11, far outstripping what can be done with the biggest telescopes on the ground."

> "BEFORE HUBBLE, WE KNEW ESSENTIALLY NOTHING ABOUT GALAXIES IN THE FIRST HALF OF THE LIFE OF THE UNIVERSE" GARTH ILLINGWORTH

Although Hubble is best known for the spectacular images taken with its cameras, these are complemented by other, equally important instruments in the form of spectrographs. The latter add a whole new dimension, as Hubble's senior project scientist Jennifer Wiseman explains. "The spectrum taken with the STIS spectrograph on Hubble tells you about the composition of the gases and the material in the system, and the motions of the material as well. Having cameras and spectrographs gives you a very powerful combination of scientific tools."

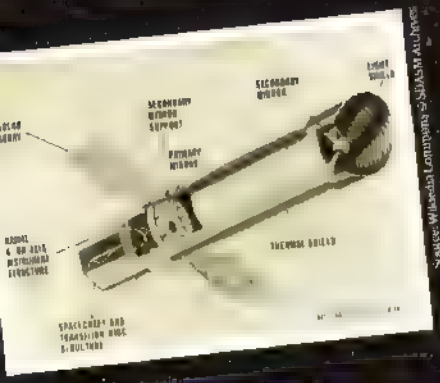
Perhaps the most dramatic use of Hubble's spectrographs – and one that few astronomers would have envisioned when it was launched 30 years ago – is in exploring the atmospheres of recently discovered exoplanets around distant stars. "This technique called transmission spectroscopy has been leveraged about 100 times," explains

THE MAKING OF A SPACE TELESCOPE

1970

Launch minus 20 years

NASA's aspirations to launch a 'large space telescope' go back a long way, and this 1970 conceptual drawing already looks distinctly Hubble-like.



1985

Launch minus 5 years

By early 1985 Hubble was finished and scheduled for launch the following year – then it was delayed by the tragic Challenger accident in January 1986.

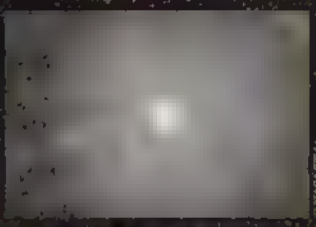
APRIL 1990

The good news ...

After a four year wait, Hubble was finally blasted into space on board Space Shuttle Discovery on 24 April 1990, blasting off from the Kennedy Space Center.

... and the bad news

Within weeks of launch it became clear there was a serious problem with Hubble's optics. Stars that should have been sharp pinpoints looked horribly blurred.



Another rescue mission

By late 1999 a series of gyro failures meant Hubble needed more repairs – carried out by, among others, British-born astronaut Michael Foale, seen in action below.

In-service upgrade

Another servicing mission installed two new scientific instruments, the Space Telescope Imaging Spectrograph (STIS) and Near Infrared Camera and Multi-Object Spectrometer (NICMOS).

Shuttle to the rescue

A complex repair mission got Hubble working the way it was supposed to. The photo below shows astronauts wrapping up after five days of spacewalks.

MARCH 2002

A new camera

The fourth servicing mission saw the last of Hubble's original instruments replaced with this one – the Advanced Camera for Surveys (ACS).

DECEMBER 1999

The final servicing mission

The Space Shuttle's last visit to Hubble, involving a thorough overhaul, was almost 11 years ago – the last time anyone saw it at close quarters.

FEBRUARY 1997

Pillars of Creation redux

Improvements made during the servicing missions meant that when Hubble revisited one of its 'greatest hits', the result was even more spectacular than the original.

DECEMBER 1993

MAY 2009

OCTOBER 2014

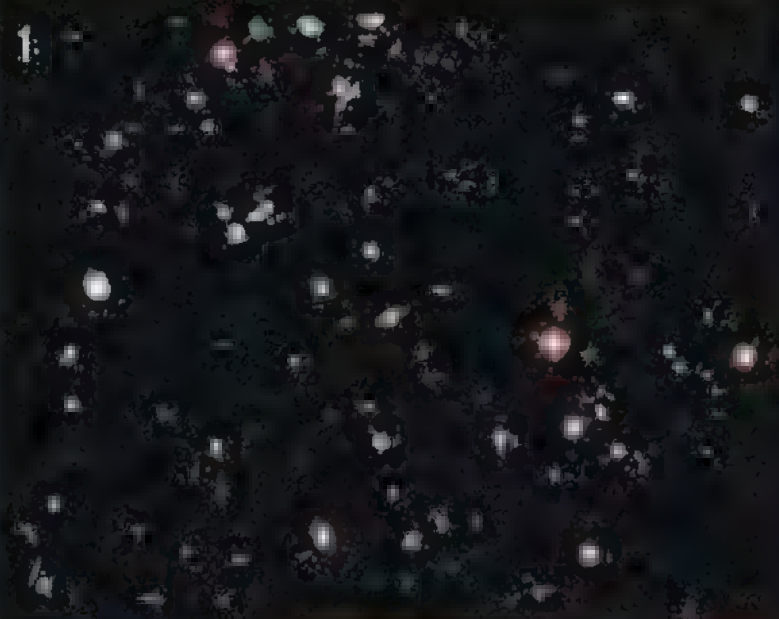
exoplanet specialist Nikole Lewis. "We can actually look at starlight filtered through those planet atmospheres to find out something about what's in the air around these planets beyond our Solar System." It's particularly exciting to find traces of chemicals which, on Earth, we associate with life – water being the most obvious one. Hubble made headlines in 2019 with the first discovery of water in the atmosphere of an Earth-like exoplanet – in this case K2-18b which orbits in the habitable zone of a red dwarf star.

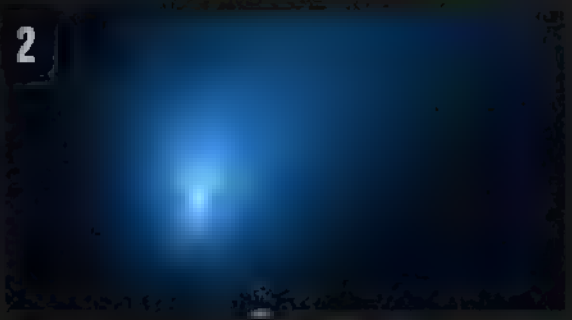
In its 30 years in space, the Hubble Space Telescope has contributed to every aspect of astronomy – from our own Solar System to the most distant galaxies – and more than 15,000 scientific papers have been published detailing its results. These include many exciting new discoveries,

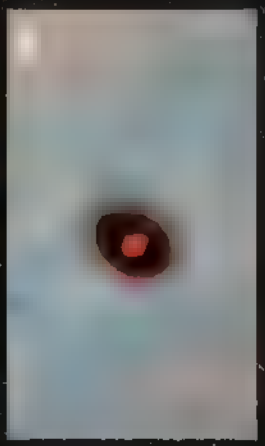
Right: A photograph from March 1979 showing the fabrication of Hubble's main mirror

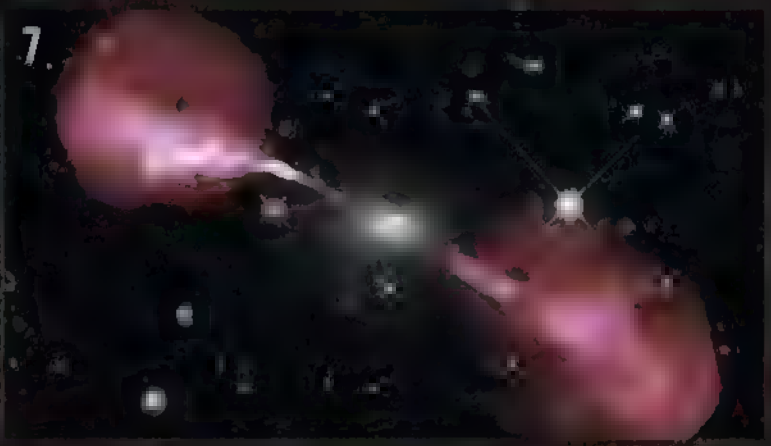
WHAT HAVE WE LEARNED FROM HUBBLE SO FAR?

The space telescope has made fascinating new discoveries in every branch of astronomy. Here are some highlights









1 This is the Hubble 'Extreme Deep Field' image released in 2012. It's a tiny area of the sky, photographed with an effective exposure time of 23 days. That means it can pick out hundreds of galaxies that are so faint – and, so distant – that they've never been seen before.

2 In October 2019 Hubble provided the clearest image yet of an interstellar comet. This is 2I/Borisov, only the second interstellar visitor to be detected after 'Oumuamua in 2017. This image was taken when 2I/Borisov was nearly 420 million kilometres (260 million miles) from Earth.

3 Hubble has given us unprecedented views of gravitationally lensed quasars – distant objects we see in distorted form due to the bending of light around an intervening galaxy. This is the 'Einstein Cross' – a multiple imaged quasar taken by Hubble's Faint Object Camera.

4 Exoplanets are usually detected by indirect methods, but Hubble can see some of them directly. This example is Fomalhaut b, orbiting its parent star amid a vast belt of debris. The star is blocked out using a coronagraph, allowing the planet to be seen.

5 Earth isn't the only planet to experience the phenomenon of aurorae – Hubble has observed dramatically scaled-up versions around the poles of Jupiter and Saturn too. This ultraviolet image of Jupiter's aurora was taken by Hubble in support of NASA's Juno mission.

6 One of Hubble's first major discoveries was the observation of protoplanetary discs – called proplyds for short – around young stars, particularly in the highly active star-forming region of the Orion Nebula. This image, released in 1995, shows just one of Orion's many proplyds.

7 One of the great things about Hubble is how it can be used in combination with other telescopes. Here's Hubble's view of galaxy Hercules A, with data from the Very Large Array radio telescope superimposed. The latter shows two jets powered by its supermassive black hole.

SPACE TELESCOPE SUCCESSOR

James Webb will be bigger than Hubble - but it's not a straight replacement

In 2003 NASA commissioned a successor to Hubble, called the James Webb Space Telescope (JWST) after former administrator James Webb, who oversaw the creation of NASA's human spaceflight program in the 1960s. The JWST will be different from Hubble in many ways. Its main mirror, instead of a single piece of glass, will be made from 18 hexagonal segments, giving it a diameter of 6.5 metres (21 feet). It will be able to see even fainter objects at even greater resolution. But it won't see them at the same wavelengths as Hubble, which spans 100 nanometres (nm) in the ultraviolet to 2,500nm in the infrared - for comparison, your eye sees from 380 to 740nm. JWST is essentially an infrared telescope, optimised for 600 to 28,000nm. It won't be able to see green or blue light, just orange and red, together with much longer wavelengths beyond that.

JWST optics
An 18-element, 6.5-metre (21-foot) mirror feeding two cameras and two spectrographs optimised for infrared.

JWST orbit
Will be located at the Sun-Earth Lagrangian point L2, approximately 1.5 million kilometres (932,056 miles) from Earth.

Hubble orbit
Orbiting 540 kilometres (336 miles) above the surface of Earth, this gives a more obstructed view than L2, but meant the Shuttle could make servicing visits.

Hubble optics
A single mirror feeding two cameras and two spectrographs with a range of capability from near-infrared to near-ultraviolet.

© Adam Mann

from the supermassive black holes lurking in the centres of galaxies to the mysterious 'dark energy' that's responsible for the accelerating expansion of the universe. One Hubble scientist, Adam Riess of NASA's Space Telescope Science Institute (STScI), was awarded a share of the 2011 Nobel Prize for his part in the discovery of this effect.

As the senior project scientist for Hubble, it's Jennifer Wiseman's job to keep track of the full range of Hubble's scientific activities in different areas of astronomy. **All About Space** asks her how things are going. "30 years into the mission, the scientific productivity of Hubble is at an all time high," she tells us. "The reason is that the servicing missions, especially the final one in 2009, have been very successful, keeping Hubble very fit for great observations and cutting-edge science. Also clever new observing techniques developed by Hubble scientists have boosted new discoveries as well. And the outstanding expert operations team on the ground - engineers, technicians, managers, and computer support - keep diligent watch over Hubble's subsystems to keep science return at a maximum as Hubble ages."

So what's the payoff for the scientific community? "Currently there are almost a thousand science papers published every year based on data from Hubble," Wiseman says. "That's more than ever before. About half of these are based on data taken from the Hubble archive. This is fantastic. It means that data originally taken for one scientific purpose is being used again for a different scientific purpose - a great return on investment!"

Some of the scientists who work with Hubble today were still at school - or not even born - when it was launched 30 years ago, while others have been closely involved with it throughout that time. In the latter category is Colin Norman, a senior staff member at STScI who was an eyewitness to Hubble's launch from Cape Canaveral in April

© NASA

Left: The Corrective Optics Space Telescope Axial Replacement (COSTAR) was key to repairing Hubble's mirror problem

WHAT THE SCIENCE TEAM LOVE ABOUT HUBBLE (CONTINUED)

"WE'RE USING HUBBLE TO INVESTIGATE BIG QUESTIONS ABOUT THE UNIVERSE [LIKE DARK ENERGY] THAT WERE NOT ANTICIPATED WHEN HUBBLE WAS ORIGINALLY LAUNCHED"

Jennifer Wiseman, Hubble senior project scientist

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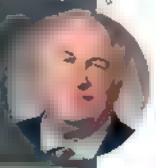
"A GAME CHANGER FOR CIVILISATION'S PERCEPTION OF THE UNIVERSE AND OUR PLACE IN THE UNIVERSE"

Ray Villard, news director for the Space Telescope Science Institute



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"THE HUBBLE TENSION BETWEEN THE EARLY AND LATE UNIVERSE MAY BE THE MOST EXCITING DEVELOPMENT IN COSMOLOGY IN DECADES"

Adam Riess, senior staff member at the Space Telescope Science Institute

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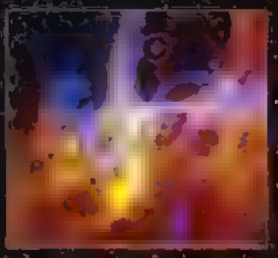
HUBBLE'S GREATEST IMAGES

1991 - 2020

1991



CYGNUS LOOP

Taken in April 2001, this image shows part of the Cygnus Loop supernova remnant, a bubble-like blast wave expanding outwards from a colossal stellar explosion that occurred some 15,000 years ago.

SATURN

You could easily mistake this photograph for a close-up image of Saturn taken by a passing space probe. The horizontal bands, caused by strong winds in the planet's dense atmosphere, are clearly visible.

RED SPIDER NEBULA

Here's another planetary nebula, NGC 6537 in Sagittarius. It's a double-lobed nebula, which despite its nickname – the Red Spider – looks more like a delicate butterfly than an arachnid in this beautiful image.

HUBBLE DEEP FIELD

This is Hubble's first 'deep-field' image taken in 1995. It's an ultra-long-exposure photograph of a tiny patch of sky, revealing hundreds of galaxies – many of them far more distant than anything that had been seen before.

ROTTEN EGG NEBULA

The 'Rotten Egg Nebula' may have an unattractive name, but it's far from unattractive, as this colourful image shows. It shows the subtle variations in physical properties of the outflowing material making up the nebula.

ESKIMO NEBULA

One of the first images taken after the third servicing mission by Discovery in December 1999, this shows NGC 2392 – better known as the 'Eskimo Nebula' for its resemblance to a human face in a furry hood.

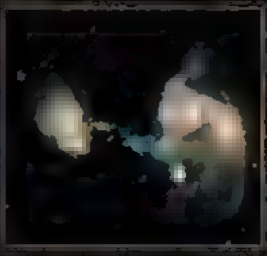
ARP 148

The anniversary image for 2008 was actually a montage of 59 pairs of colliding galaxies. Here is just one of the pairs, Arp 148, described by NASA as "the staggering aftermath of an encounter between two galaxies".

CARINA NEBULA

On the 17th anniversary of Hubble's launch in April 2007, NASA began a new tradition of releasing an official anniversary image. This first one shows the swirling clouds of gas and dust in a portion of the Carina Nebula.

2009



ARP 194

Colliding galaxies featured again in this anniversary image. Rather than a pair of galaxies, Arp 194 consists of three of them all interacting with each other. The bright blue areas are created by swarms of newborn stars.

MYSTIC MOUNTAIN

Called the 'Mystic Mountain', this image was released to mark the telescope's 20th anniversary in 2010. It shows part of the Carina Nebula – actually a tiny detail from the area covered in the 2007 anniversary image.

NGC 4302 AND NGC 4298

For its 2017 anniversary image, the Hubble team picked this dramatic view of a pair of galactic neighbours. They're almost perpendicular to each other, so we see the first of them edge-on and the other face-on.

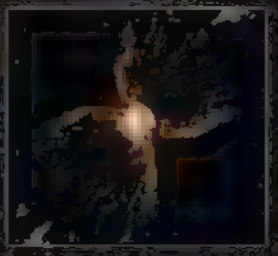
BUBBLE NEBULA

NGC 7635 is an emission nebula 8,000 light years away in Cassiopeia. Looking at this amazing photograph, released as the anniversary image for 2016, it's easy to see how it got its nickname, the 'Bubble Nebula'.

LAGOON NEBULA

A particularly colourful emission nebula featured in the 2018 Hubble anniversary image in the form of the Lagoon Nebula – Messier 8 or NGC 6523 – a giant interstellar cloud in the constellation Sagittarius.

2019



THE SOUTHERN CRAB NEBULA

The famous Crab Nebula has a lookalike in the form of an otherwise unrelated planetary nebula in the Southern Hemisphere. This 'Southern Crab Nebula' starred as the Hubble anniversary image last year.

JUPITER

This was Hubble's first full-colour snapshot of Jupiter, created by superimposing three images taken with red, green and blue filters. The Great Red Spot, a hurricane-like formation larger than the Earth, is clearly visible.

SUPERMASSIVE BLACK HOLE?

This image shows the core of the giant elliptical galaxy NGC 4261 in the Virgo Cluster, 100 million light years away. It's believed to show the hot disc of material surrounding a black hole with a mass 10 million times that of the Sun.

STARBURST RING

This shows Hubble's high-resolution view of the core of galaxy NGC 4314, which lies 40 million light years away in the constellation Coma Berenices. Clusters of infant stars are visible as bluish-purple clumps.

PILLARS OF CREATION

The first truly iconic image, this original 'Pillars of Creation' photo dates from April 1995. It shows part of the Eagle Nebula, a star-forming region 6,500 light years away in the constellation Serpens.

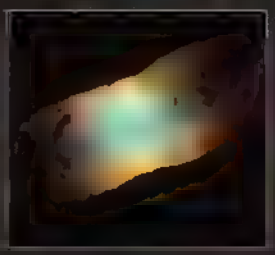
SHOEMAKER-LEVY 9

In July 1994, fragments of comet Shoemaker-Levy 9 crashed into Jupiter. This ultraviolet image taken by Hubble shows the huge scars that the impact created in Jupiter's atmosphere – larger than our own planet.

2001

RETINA NEBULA

Here's another gorgeous planetary nebula, IC 4406, in the Southern Hemisphere constellation of Lupus. It's been dubbed the 'Retina Nebula' due to its resemblance to the retina of a human eye.



HELIX NEBULA

Here's another strikingly eye-like planetary nebula – this time the Helix Nebula, NGC 7293 in Aquarius. A 'mere' 690 light years away, it's one of the closest planetary nebulae to Earth – and one of the most striking.

ANTENNAE GALAXIES

NGC 4038 and NGC 4039 are in the process of colliding with each other – albeit on an enormously slow timescale. The increased gas density where they overlap leads to the creation of billions of new stars.

WHIRLPOOL GALAXY

If you're an amateur astronomer you'll be familiar with the Whirlpool Galaxy – M51 in Canes Venatici. But you'll never have seen it with the amazing clarity of this image, released to celebrate Hubble's 15th anniversary.

'STARRY NIGHT'

Two years before this photo was taken, supergiant star V838 Monocerotis gave off a sudden pulse of light, creating an expanding halo of light around it. This image is likened to van Gogh's famous painting *Starry Night*.

A GALACTIC ROSE

For Hubble's 21st birthday in 2011, NASA released this lovely picture of another pair of interacting galaxies, Arp 273, in a composition that looks uncannily like an impressionistic painting of a rose.

TARANTULA NEBULA

A region of ionised gas in the Large Magellanic Cloud, low-resolution photos taken by Earth-based telescopes do look a little like the giant spider after which it's named, but any resemblance is lost in this detailed view.

2012

CELESTIAL FIREWORKS

For Hubble's 25th anniversary, NASA released this image of Westerlund 2. The cluster contains some of the galaxy's hottest and brightest stars, which etch away at the enveloping gas cloud with torrential stellar winds.

MONKEY HEAD NEBULA

The same constellation that hosts the Horsehead Nebula, Orion, also boasts a less well-known feature nicknamed the 'Monkey Head Nebula' – an emission nebula formally known as NGC 2174.

HORSEHEAD NEBULA

Like the Whirlpool Galaxy, the Horsehead Nebula is another favourite sight for amateur astronomers. It looks dramatically different, however, when viewed in infrared light – as in this Hubble anniversary image.

2020

RUBIN'S GALAXY

As Hubble's 30th anniversary approached, NASA released this majestic image of the galaxy UGC 2885 in January 2020. A veritable giant, it's been designated Rubin's Galaxy after the astronomer Vera Rubin.

1990. We ask him to sum up his feelings about the last 30 years: "Hubble has changed the landscape of astronomy and astrophysics," he tells us. "It has far exceeded its early goals – no other science facility has ever made such a range of fundamental discoveries. It's been a privilege to be associated with this effort that has become embedded in the culture of our time."

That last point is an interesting one. For all its groundbreaking scientific discoveries, Hubble's most unique achievement is arguably the inspirational impact it's had on the general public. It would be an understatement to say it's the most famous telescope in history. Before Hubble, people without a special interest in astronomy probably couldn't have named a single telescope. Yet today, Hubble is a household name, instantly recognisable to people all over the world and a symbol of both the brilliance of human ingenuity and the wonders of the universe.

What's the reason for Hubble's uniquely iconic status? Ray Villard, STScI's news director, thinks he has the answer. "It reads like a movie script; it has a story arc," he says. "The anticipation of launch, the optical failure, redemption with the servicing missions – then more drama when it was cancelled in the last decade." Fortunately that cancellation was averted, and Hubble is still with us – hopefully for many years to come. As Villard says, "Well towards 2030 we're back to doing some of the best science we think we can ever do with Hubble."

© Adrian Mann

MIKE MASSIMINO: "I'D BROKEN HUBBLE AND I WAS ALONE IN SPACE"

Mike Massimino had made a huge error. What's more, he didn't have backup while his fellow astronauts looked on

Mike Massimino and fellow astronaut Mike Good were completing a spacewalk where they sought to repair Hubble's imaging spectrograph, an instrument used to detect far-off planets and black holes. More than 100 new space tools were developed for the spacewalk, but Massimino ended up yanking a handrail away with his hands. It had been blocking the access panel to the power supply, but one of the screws was stripped, making it impossible to come off. He did this while zipping the Earth at 28,164 kilometres (17,500 miles) per hour.

"We were going to use a large number of tools during a mission to repair the failed power supply of Hubble, and we had practised it for years. Although the two bolts on the top of a handrail that covered the access panel came off with no problem, the bolt on the bottom right did not. Instead, the head of the bolt was stripped out, and when I took a closer look, I spun my tool inside of it and destroyed any chance of being able to undo that screw. This meant the handrail wasn't going to come off and I wasn't going to be able to get to the main electronics board. This meant we were never going to be able to replace the power supply, never get Hubble back running and never find out there was life on other planets – and I was going to be blamed. That was pretty much my thought process, but the team on the ground started to troubleshoot and I started trying not to make things worse in space.

It took them about an hour or so to come up with a solution – and that time felt like an eternity out there. All the while the Sun's coming up and down and I'm wondering whether sooner or later we're going to have to knock it off and come inside because we were running out of time. But then they told me to get some tape and vice grips: I could understand vice grips because that was a tool. Tape, on the other hand, made me think we were running out of ideas. But someone had the idea of just seeing if I could yank this thing off, and they'd worked out that about 60 pounds of force was required.

I did just that, grabbing some tape from the toolbox at the front of the Space Shuttle before heading back to use it on the bottom of the handrail. I felt a deep loneliness because there was no one to help me at that specific time, but I taped the handrail, put my hand on it and knew that the reason I was using that tape was because there would be a real worry if any debris got loose. I pulled.

I managed to rip the handrail away; got it right off. I could then get to the access panel, but my power tool's battery had gone and I was also needing an oxygen refill. I put my fears aside, got more oxygen and swapped out the battery before getting on with the task. The screws came out, the new power supply went in and it worked – a successful mission from a position higher than the Space Station – and the instrument had come back to life. I then just looked at the Earth from 350 miles [563 kilometres] up.

I was out there in space, all by myself, with my own life-support system, and I could look anywhere I wanted. I could look and see the planet from where Hubble is. I thought, this would be the view from heaven. But then, I thought, it was more beautiful than that. It was like looking into a paradise. Getting to see the planet and the stars on a spacewalk was truly an incredible experience."

Right: Mike Massimino flew on the fourth Hubble servicing mission, STS-109

RISE OF THE


UNITED STATES SPACE FORCE
DEPARTMENT OF THE AIR FORCE
MMXIX

Signed into law in 2019, what will this new branch of the US military actually do?

Reported by Jonathan O'Callaghan

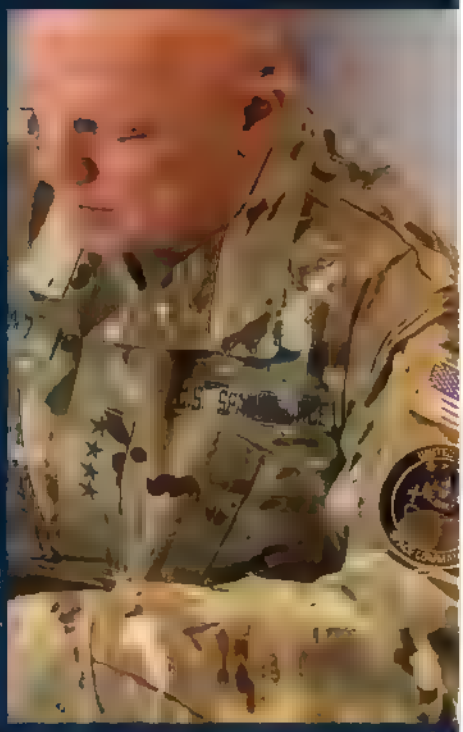
The idea of a space force sounds a bit bizarre. Why do we need a branch of the military protecting us from space? While the reasoning behind it might not be to everyone's liking, there is actually a purpose for a space force. And while it won't be protecting us from evil invading aliens heading to our planet, it is designed to potentially address conflicts in space – a type of warfare that might indeed be alien to many.

The United States Space Force (USSF) is a branch of the US Armed Forces first announced by President Trump in mid-2018. Trump said the force was intended to protect "American dominance in space". His former secretary of defense, James Mattis, referred to space as a "warfighting domain" and said the US needed to be wary of other countries acting in space. They decided the best way to deal with this was by a show of strength. Trump formally established the Space Force as a new branch of the US military in December 2019. It has its own logo and its own head, General John Raymond, who is the agency's chief of space operations. At the time of writing, plans are afoot to change the names of key bases in the US over to the Space Force. Cape Canaveral Air Force Station looks set to become the Cape Canaveral Space Force Station, while the Vandenberg Air Force Base could become the Vandenberg Space Force Base.

By and large, the Space Force appears to be an attempt to turn what was a very offhand comment by Trump two years ago into actual policy. "Congress took a seemingly flippant remark and created a rational implementation plan, a Space Force to support Space Command," Joan Johnson-Freese, a professor of national security affairs at the Naval War College in Newport, Rhode Island, said earlier this year. "Whether it will evolve into an organisation that solves any of the problems that prompted it remains to be seen. On the negative side, it certainly increases the perception that the US is leading the way in the weaponisation of space."

American military operations in space are broad. They include operating satellites, performing tests and keeping an eye on the activities of several rival countries in space, notably China and Russia. In February 2020 it was revealed by General Raymond that a Russian satellite had been tailing a US spy satellite in space, for example. Approaching to just 160 kilometres (100 miles) from the US satellite, it was believed Russia was spying on the US satellite and taking a look at how it worked. "We view this behaviour as unusual and disturbing. It has the potential to create a dangerous situation in space," Raymond said at the time.

Below: Trump signed the National Defense Authorization Act in late 2019 to make the Space Force a reality



Prior to the creation of the Space Force, US activities in space were handled by the US Air Force, more specifically Air Force Space Command. This included the management of launch complexes in the US and more intricate details like the tracking of satellites in space. Now that the Space Force has been created, it's believed that many of these activities will shift over to the new branch of the US military. But many aspects, such as space military research and funding, remain unclear as to how they will progress – the US Department of Defense (DOD), for example, has been very slow to relinquish control of the Space Development Agency. The plan is to shift it over to the Space Force by late 2022.

About 60 different parts of the US military are currently involved in space, while Air Force Space Command boasts about 36,000 people. The idea is that the Space Force could take over many of these operations, providing one single hub to tackle all areas and bring people from different branches together. Some have questioned why a Space Force is needed at all when these parts of the US military already function with few issues, but others have noted a greater need to unify everything under one roof. And the US is not alone in having a space force – Russia, for example, has boasted its own Russian Space Forces since the 1990s.

There is still the question, however, of what the Space Force will do exactly. It will not be fighting aliens in space, despite having its own uniform. It will, however, try and tackle some of the growing concerns about space activity in order to protect many of the US assets currently in space. There are concerns that some countries or rogue organisations might possess anti-satellite technology – for example, able to shoot down satellites using missiles or even powerful lasers. The Space Force will be tasked with making sure that doesn't happen.

It's unlikely, however, that the Space Force will have much involvement with NASA. While the latter does occasionally cooperate with the Air Force on space matters, the two are mostly separate, with NASA focusing on scientific space activities. It's likely that the Space Force will continue in the same manner, with some minimal cooperation with NASA, perhaps on launches and other matters, but

SPACE FORCE UNIFORMS

Mocked slightly at their unveiling, here is what the personnel are likely to wear

The same for all

Space Force uniforms are standardised for everyone in the force so that they are easily recognisable from other branches of the military.

Camouflage in... space?

The use of camouflage on the uniform might be surprising, but this is just keeping it in line with the design of the Army and Air Force.

Space Command

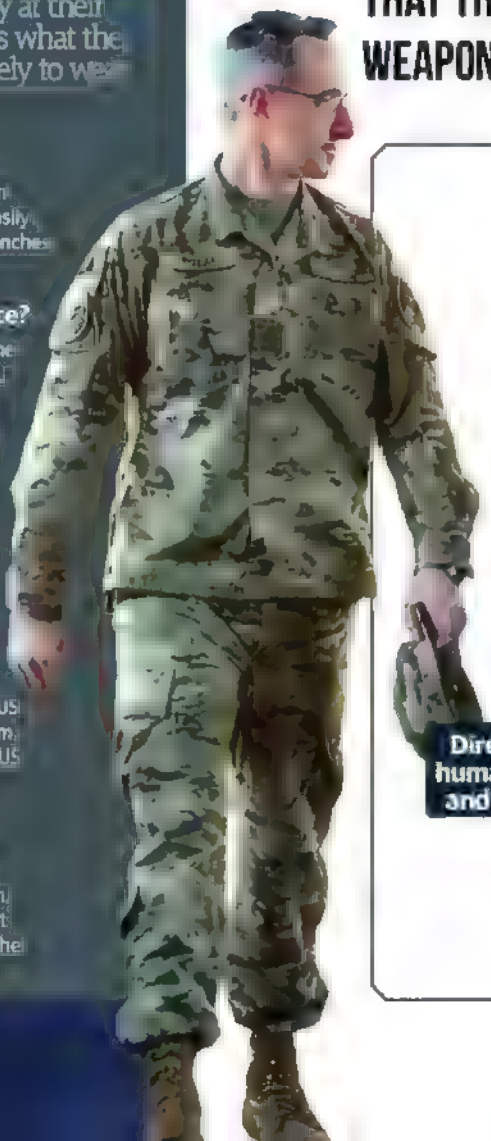
A badge is visible on the sleeve denoting this part of the military that was formed around the same time as the Space Force.

American flag

The stars and stripes of the US flag are visible on the uniform, which is the same across all US military uniforms.

Branch identifier

The text 'US Space Force' is clearly visible on the uniform, just in case anyone might get confused with members of the other military branches.



"IT CERTAINLY INCREASES THE PERCEPTION THAT THE US IS LEADING THE WAY IN THE WEAPONISATION OF SPACE"

OFFICE OF THE CHIEF OF SPACE OPERATIONS

Here's how the upper echelons of the Space Force will be structured

- Chief of space operations
- Vice chief of space operations
- Director of staff
- Director for human capital and logistics
- Director for operations, cyber and intelligence
- Director for plans, programs, requirements and analysis

WHAT ARE THE AIMS OF THE SPACE FORCE?

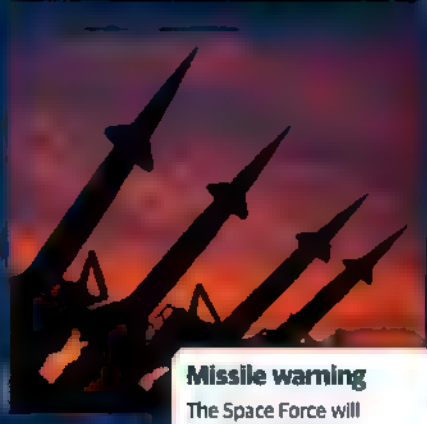
What does the department actually plan to do, and how does it plan to do it?

Command and control of satellite operations

Assets like GPS will be looked after by the Space Force to make sure that the US doesn't lose access to some of its important space capabilities.

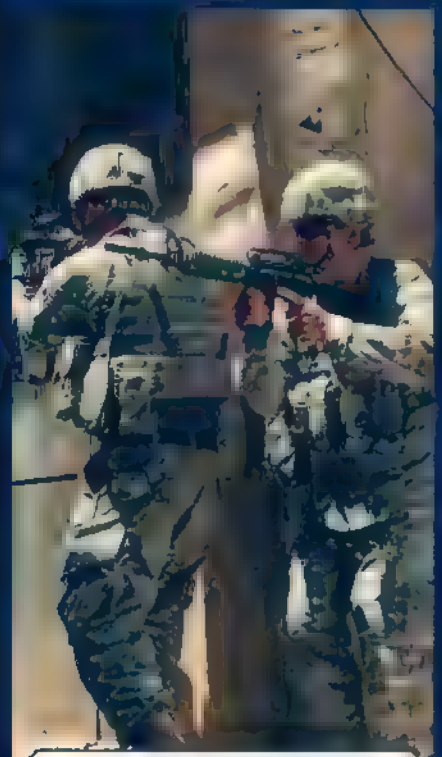
Space domain awareness

The Space Force will track and monitor satellites in orbit and try to make sure they are not at risk of colliding with any others.



Missile warning

The Space Force will continue developing satellites to monitor any missile launches that might threaten the US, its forces deployed around the world or any of its allies.



Space support to operations

This includes making sure that military services on the ground that rely on space-based capabilities, like satellites, are not interrupted and continue operating.

Space superiority

The Space Force is designed to make sure the US remains a leader in all space activities. This means having continuing access to space, including the launch and operation of satellites.

WHO'S INVOLVED?

At the moment the Space Force has only one member, but thousands more are expected to follow

General John Raymond

Role in Space Force: chief of space operations

General Raymond is in charge of leading the US Space Force, being its first chief of space operations. He was announced in the role by President Trump in 2019, and is now in charge of getting the fledgling branch up and running.

Below: There is a lot of space debris orbiting Earth that needs to be tracked

for the most part the two will be kept separate from each other.

As mentioned earlier, the Space Force will likely also be responsible for managing many of the launch operations in the US – more of a bureaucratic switch than anything. It may also take over the running of key space research programs in the future. The Air Force, for example, has been busy developing a mysterious space plane called the X-37 for the last two decades. In the future projects like this may be more directly handled by the Space Force, which some might argue would make sense anyway. Why is the Air Force conducting tests in Earth orbit in the first place?

The Space Force is expected to have a budget of $2 billion over the next five years, with roughly 15,000 personnel expected to transfer over to it from other branches of the US military. However it's not yet clear how or when people will be able to apply to enlist in the Space Force, or whether that will even be possible. Will it have recruitment centres like the Air Force? That's another major unknown about how it will operate. It's also not clear if soldiers will be trained within the Space Force, like other branches of the military.

However, we do have a vague idea of what it will do, namely taking all the other space activities from other branches of the US military and bringing them together. It will be headquartered at the Pentagon and initially will be part of the Air Force before becoming its own true branch at the end of 2020. According to a 'fact sheet' released by the US government in 2020, the Space Force "is a military service that organizes, trains and equips space forces in order to protect US and allied interests in space and to provide space capabilities to the joint force. USSF responsibilities include developing military space professionals, acquiring military space systems, maturing the military doctrine for space power and organizing space forces to present to our Combatant Commands."

According to the fact sheet the Space Force will also "maintain and enhance the competitive edge of the DOD in space while adapting to new strategic

"IT'S LIKELY THAT THE SPACE FORCE WILL CONTINUE IN THE SAME MANNER, WITH SOME MINIMAL COOPERATION WITH NASA, PERHAPS ON LAUNCHES AND OTHER MATTERS"

challenges" One example of this is the Global Positioning System (GPS), a small constellation of satellites that provides positional data not only to users on the ground, but to the military as well. Were GPS to be targeted it could have major impacts on how the US conducted its own ground operations, and potentially halt them entirely

The Space Force will also take over the monitoring of positional data for satellites in orbit, currently handled by US Strategic Command. This allows satellites orbiting Earth to avoid collisions with each other – by keeping track of where satellites are, the US military can alert any satellite operators if they are on a potential collision course with another satellite. This capability is vital to making sure Earth orbit remains usable by countries and companies, preventing collisions that cause large amounts of debris. And according to the Space Force's published goals, this is one of the areas it will be responsible for

Similarly the US operates a number of reconnaissance satellites in orbit along with other military hardware. The Space Force will most likely be tasked with operating these satellites, or at least ensuring they remain in service. These satellites allow the US to peer into other countries, returning images of extremely high resolution of distant targets. They are a vital part of the US military's activities around the world, and if someone were to try and take them out, there could be severe consequences for how the military operates. It makes sense they'd like to keep them relatively safe

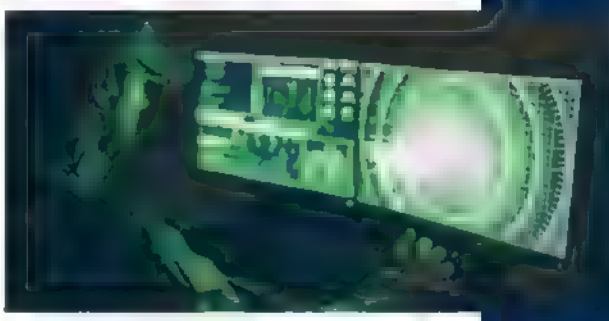
The Space Force will not, however put people into space. Contrary to its name, it will not involve any sort of human fighting force being sent into orbit or beyond. While there has been discussion that the Space Force could be involved in some futuristic aspects of space exploration, such as asteroid mining, there are no current plans to actually send anyone to space. Don't expect to see any Space Force personnel suddenly popping up on the International Space Station'

The main purpose of the Space Force is to bring all the spacey goodness of the US military together However, there have been some concerns that its very creation is somewhat an act of aggression against others in space. By proclaiming space as a "warfighting domain", the US has quite clearly drawn battle lines – a little ironically however, if there was actually a war in space, this would be handled by US Space Command not the Space Force. With Russian satellites already performing questionable operations in orbit, and China rapidly expanding its space activities, the potential for some sort of conflict to erupt in space, and possibly feed down to Earth, is ever-present.

"Space is the world's newest warfighting domain," Trump said at the signing ceremony for the Space Force in December 2019. "Amid grave threats to our national security American superiority in space is absolutely vital. And we're leading, but we're not leading by enough. But very shortly, we'll be leading by a lot. The Space Force will help us deter aggression and control the ultimate high ground."

And in a statement General Mark Milley, chairman of the joint chiefs of staff, laid out some of the reasoning behind the Space Force. "Our adversaries are building and deploying capabilities to threaten us, so we can no longer take space for granted," he said. "The US Space Force is the necessary and essential step our nation will take to defend our national interests in space today and into the future."

Whether that is really true is up for debate, but like it or loathe it, the Space Force is already here, and it's not going anywhere anytime soon. It might not quite be the dawn of laser battles in space, but it does herald the beginning of a new era where countries become increasingly nervous about their sensitive assets in space. And if everyone can't get along nicely, maybe something like the Space Force will be necessary. For the time being it is simply a bureaucratic reshuffling of US space activities and many hope it will remain that way for the foreseeable future



Top: The Space Force will track and monitor satellites orbiting Earth to prevent collisions

Above: Many US military operations rely on space capabilities to be successful

DO WE REALLY NEED A SPACE FORCE?

For: Space is absolutely vital to the US, and to its military capabilities. It relies heavily on satellites to provide images and communications for its military on the ground, and if another country or rogue actor were to threaten this capability, it would be disastrous. Having a branch of the military to protect all space activities seems to make sense.

Against: Many feel that space should be used for peaceful purposes, not for militaristic ones. While the military does makes use of space, any escalation of tensions in Earth orbit could be disastrous. Creating the Space Force may only make the chance of conflict in space, rather than peaceful resolution to any disagreements, more likely.

11 MISSIONS THE WORLD DOESN'T KNOW ABOUT

Away from the biggest names, there are some exciting plans in the pipeline from companies and agencies around the world

Reported by Lee Cavendish

What are the first names that spring to mind when you think of space exploration? NASA? SpaceX? The European Space Agency? That's completely reasonable, seeing as they are making tremendous strides forward in this field. However, space is not restricted, and there are companies and agencies from a variety of countries that have their own plans, ideas and visions for the future.

In 2018 the global space economy was estimated to be worth £319 billion ($447.5 billion), and that figure is only going to grow. With companies offering easier and more affordable rides into space, the number of satellites in low-Earth orbit is growing by the week, and countries and enterprises are also realising that it's an industry that simply can't be ignored. No one can be expected to know all the goings-on from around the world, so here we present a selection of 11 lesser known, but equally exciting projects that are looking to make a real impact in the new decade.

PERIGEE AEROSPACE WILL TEST ITS BLUE WHALE 1

A relatively unknown aerospace company from Daejeon, South Korea, is looking to unleash its own small launcher, with a maiden spaceflight scheduled for July 2020 (though it hasn't happened yet). This start-up has been developing a two-stage rocket called Blue Whale 1, and when operational it will be capable of transporting a 50-kilogram (110-pound) payload to a Sun-synchronous orbit.

Perigee Aerospace has claimed that Blue Whale 1 will be the smallest launcher in the world, standing at just 8.5-metres (28-feet) tall. The Atlas V two-stage rocket, which is renowned for its launches in the US, towers over it at 58 metres (190 feet). This tiny package packs a real punch though, and it can carry small payloads into low altitude, high-inclination orbits, which is ideal for weather, remote-sensing and imaging satellites.

2 THE 'INTERNET OF THINGS' CONSTELLATION

US-based company SpaceX has begun launching its Starlink constellation, which consists of a number of satellites that will eventually provide worldwide internet access. Obviously it helps if you have your own rockets to launch them, and even more so if you have a billionaire entrepreneur backing you.

There are many other companies who are looking to pull off a similar endeavour, and one of these, Sky and Space Global, is currently waiting for the funds to complete its 'Internet of Things' constellation.

Sky and Space Global, an Australian company with branches in the UK, Poland and Israel, plans to place 200 CubeSats into low-Earth orbit to provide low-data-rate communications. The short-term goal is to raise £8.3 million ($10.8 million) in order to get an initial eight satellites into orbit. If the finances become available, Sky and Space Global said it wanted to launch its satellites, nicknamed 'Pearls', by the end of 2020 (which hasn't happened yet). These satellites will provide high-quality voice and data communications and will be equipped with autonomous collision-avoidance software.

Below: Financial instability has moved the Pearl launches to the end of 2020 (but there has been no further news of this).

Sky and Space Global currently has three prototypes in orbit around Earth, which it refers to as the 'Three Diamonds'.

3 NEXT-GEN HEAVY-LIFT LAUNCHER: VULCAN CENTAUR

Move over Delta IV and Atlas V: there's going to be a new player in town. United Launch Alliance, which operates the two aforementioned launchers, is now creating a two-stage heavy-lift rocket that will improve the capabilities of the US and its national security launch needs. United Launch Alliance aims to take the rocket designs from its hugely successful Delta IV and Atlas V rockets and incorporate new technologies that will provide more reliable and affordable launches.

One of the new additions to the Vulcan Centaur is the use of two Blue Origin engines in the first stage. The BE-4 engines, surrounded by up to six booster rockets, will provide the next generation of space launches. There is also talk of an additional Advanced Cryogenic Evolved Stage (ACES), which will allow operation in space for weeks instead of hours.

© United Launch Alliance

Right: Virgin Orbit could deploy payloads into space from spaceports all over the globe

Left: United Launch Alliance has launched missions such as NASA's Curiosity rover, New Horizons and OSIRIS-REx

Collectively the two stages will use ten engines that will burn light hydrocarbons and liquid oxygen.

© Isar Aerospace

Right: Commercial operations for Spectrum could commence as early as 2022

ISAR AEROSPACE'S SPECTRUM

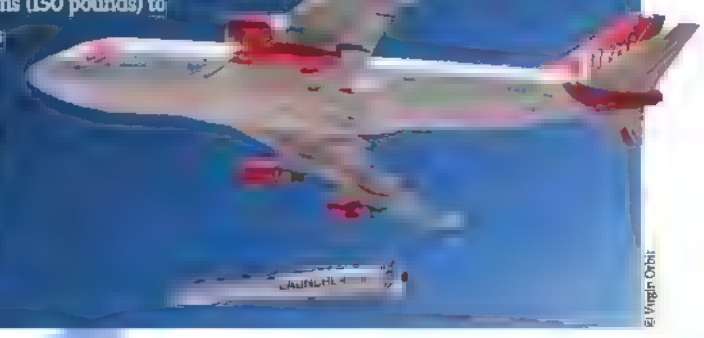
German start-up Isar Aerospace is developing its own two-stage rocket that is designed to launch satellite constellations into orbit. Its Spectrum will have the power to take 1,000 kilograms (2,200 pounds) to low-Earth orbit, and it's being developed at tremendous speed. Although the company only formed recently in 2018, it believes Spectrum could have its first taste of space at the end of 2021.

This efficiency is possible because of the backing of Airbus Ventures and other investors providing £13 million ($17 million) in funding. When it's assembled the Spectrum rocket will stand at 27 metres (89-feet) tall. It will have a system similar to SpaceX's Falcon 9 in terms of engine configuration. Spectrum will have nine first-stage Aquila SL engines, and the second cryogenic stage will have a single Aquila VAC (vacuum) engine. Daniel Metzler, Isar Aerospace's chief executive, has stated that they would like the first stage to be reusable, but at the moment the focus is on creating an expendable design which can hopefully provide 15 launches per year.

5 VIRGIN ORBIT SATELLITE LAUNCHER

Sir Richard Branson's Virgin Galactic is gaining a lot of momentum in the space tourism world, which isn't much of a surprise when you consider the public interest in the project. However, its sister company, Virgin Orbit, is also making great strides in becoming a satellite launcher. Instead of the usual two-stage vertical rocket, like Spectrum, H3 and others mentioned here, Virgin Orbit will launch horizontally, with a two-stage rocket, LauncherOne, strapped onto a modified Boeing 747-400 aircraft, Cosmic Girl.

Upon launch, Cosmic Girl will ferry LauncherOne to an altitude of 11,000 metres (35,000 feet), where the rocket will be dropped, then carrying a payload of between 300 and 500 kilograms (660 and 1,100 pounds) into orbit. The Virgin Orbit team is also in the process of introducing a third stage to the rocket that will launch interplanetary missions. This third stage could take 50 kilograms (110 pounds) to Mars, 70 kilograms (150 pounds) to Venus or over 100 kilograms (220 kilograms) to the Moon. The first flight of Virgin Orbit's LauncherOne could occur in early 2020, but that is assuming that everything goes to plan and its construction stays on schedule.



© Virgin Orbit

6 THE COLLECTIVE POWER OF CUBESATS

It's never been cheaper or easier to launch CubeSats and nanosatellites into space. Here are some reasons why they are a fan favourite

£31,000 ($40,000)

Cost to launch a CubeSat, a fraction of what it would cost to launch a large satellite.

5 MAY 2018

The first set of CubeSats to make the journey beyond Earth were NASA's Mars Cube One (MarCO) twins, which accompanied the space agency's InSight lander on its voyage when they were launched.

WALL-E & EVE

The MarCO CubeSats were nicknamed after characters from the 2008 Pixar film *WALL-E*.

BENEFITS

They improve global communications and navigation, but also monitor the changing climate and any global disasters.

1,200+

Of these launched CubeSats, over 1,100 have been successfully deployed.

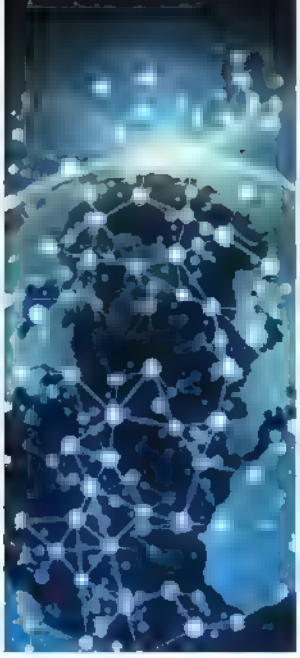
10^3

The basic dimensions of the cube, from which CubeSat gets its name, is just ten centimetres (four inches) in height, width and depth.

7 PROJECT KUIPER WORKS TOWARDS A GLOBAL INTERNET

Amazon plans to launch a satellite mega-constellation that will provide internet to tens of millions of people around the globe. This audacious project, nicknamed Project Kuiper, is aiming to put 3,236 satellites into three set of orbits at altitudes of 590, 610 and 630 kilometres (367, 379 and 391 miles).

The company's AWS Ground Station unit will have 12 facilities scattered over the world, which is vital for the ground-to-space communications. The mega-constellation will be able to gift its low-latency, high-speed broadband connectivity to people between the latitudes of 56 degrees north and 56 degrees south, restricted by the orbits of the thousands of satellites. There hasn't been a timeline stated for this project other than that it's long-term.



© Getty

Right: Portugal is a large coastal country bordering Spain and the Atlantic Ocean

8 PORTUGAL'S SECURITY SATELLITES

Portugal's recently assembled space agency is thinking long and hard about what its initial plans and objectives should be. There have been in-depth discussions about whether it should construct its own spaceport, but because of its access to the Atlantic Ocean and closeness to the equator, it makes perfect sense. The space agency is also strongly considering launching a constellation of satellites so that it can keep a watchful eye on the maritime activity in the Atlantic Ocean.

This constellation would be less focused on providing citizens of the world with internet and is more about protecting the countries of the world that have a sea border. With this constellation, Portugal will have an advantage when it comes to clamping down on coastal crimes such as illegal fishing, maritime piracy and ocean pollution. There isn't any definitive plans for this fleet of space-based security satellites, but the agency has stated that it wants to be a real authority over the Atlantic region.

© NASA

Portugal is looking to stamp itself into the space industry with its recently announced 'Portugal Space 2030'.

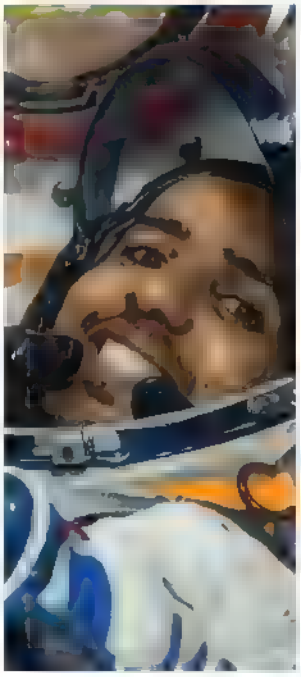
9 A FLEET OF UNITED ARAB EMIRATES ASTRONAUTS

Right: Hazza Al Mansouri became the first Emirati astronaut in September 2019 as part of the Soyuz MS-15/12 mission

Left: Internet access has recently become a global necessity, as opposed to more of a privilege

The United Arab Emirates (UAE) has shown increasing interest in the world of space exploration, with it creating its own space agency in 2014. The country has stated that it is open to the introduction of Virgin Galactic operations, and is also planning its own missions to space. Recently the UAE saw its first astronaut emerge when Hazza Al Mansouri visited the International Space Station (ISS) in September 2019.

Now the country is planning to assemble its own astronaut corps, training a selected number of people from a staggering number of applicants. The Emirati space agency announced its plans for an astronaut corps in 2017 and recently announced that there have been more than 4,000 applicants. The ages of the applicants range from 17 to 67, and over a third of them were women. This shows promising signs for the country as it looks to build a sustainable programme that has a constant string of Emiratis in space contributing to scientific research and future missions.



© NASA

10 JAXA AND MITSUBISHI'S H3 ROCKET

The H3 rocket could launch 11,900 kilograms (26,200 pounds) to the proposed Lunar Gateway or 28,300 kilograms (62,400 pounds) to low-Earth orbit.

Japanese engineers are aiming to make H3 'the world's quietest launch' by utilising sound-absorbing walls and paying close attention to noise in testing.

MHI is developing a set of inspection protocols that could narrow the idle period between rocket launches to just 30 days.

"THE BE-4 ENGINES, SURROUNDED BY UP TO SIX BOOSTER ROCKETS, WILL PROVIDE THE NEXT GENERATION OF SPACE LAUNCHES"

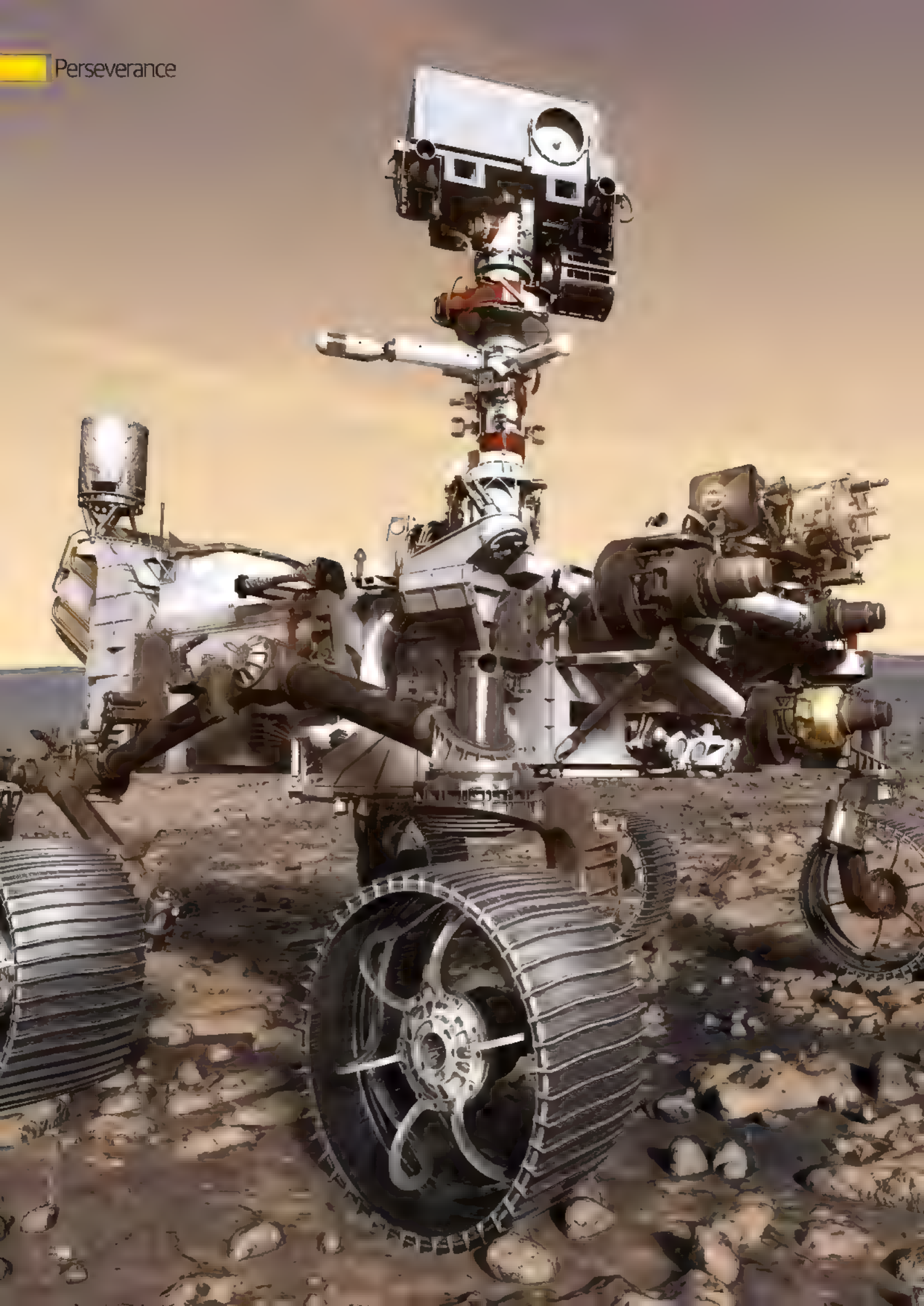
11 THE UAE'S HOPE MARS MISSION

There's a truly historic mission that launched in July 2020 that is going under the radar: the Hope Mars Mission, also known as the Emirates Mars Mission. This UAE-funded mission is the first interplanetary mission by the UAE and by any Islamic country. When Hope Mars arrives at the Red Planet in 2021, it will also coincide with the 50th anniversary of the formation of the UAE.

In terms of science and engineering, this mission, a Mars orbiter, is being built at the Emirati's Mohammed bin Rashid Space Centre, in collaboration with the University of Colorado, University of California, Berkeley, and Arizona State University, all in the US. The spacecraft will have three state-of-the-art instruments that will provide unprecedented information about the planet's weather and atmospheric history. This will hopefully provide some answers in regards to what Mars' atmosphere was like billions of years ago, what is driving out the hydrogen and oxygen from the atmosphere and how the atmosphere varies over the course of a year, season or even a day.

Right: The UAE announced its Mars mission back in July 2014

Perseverance

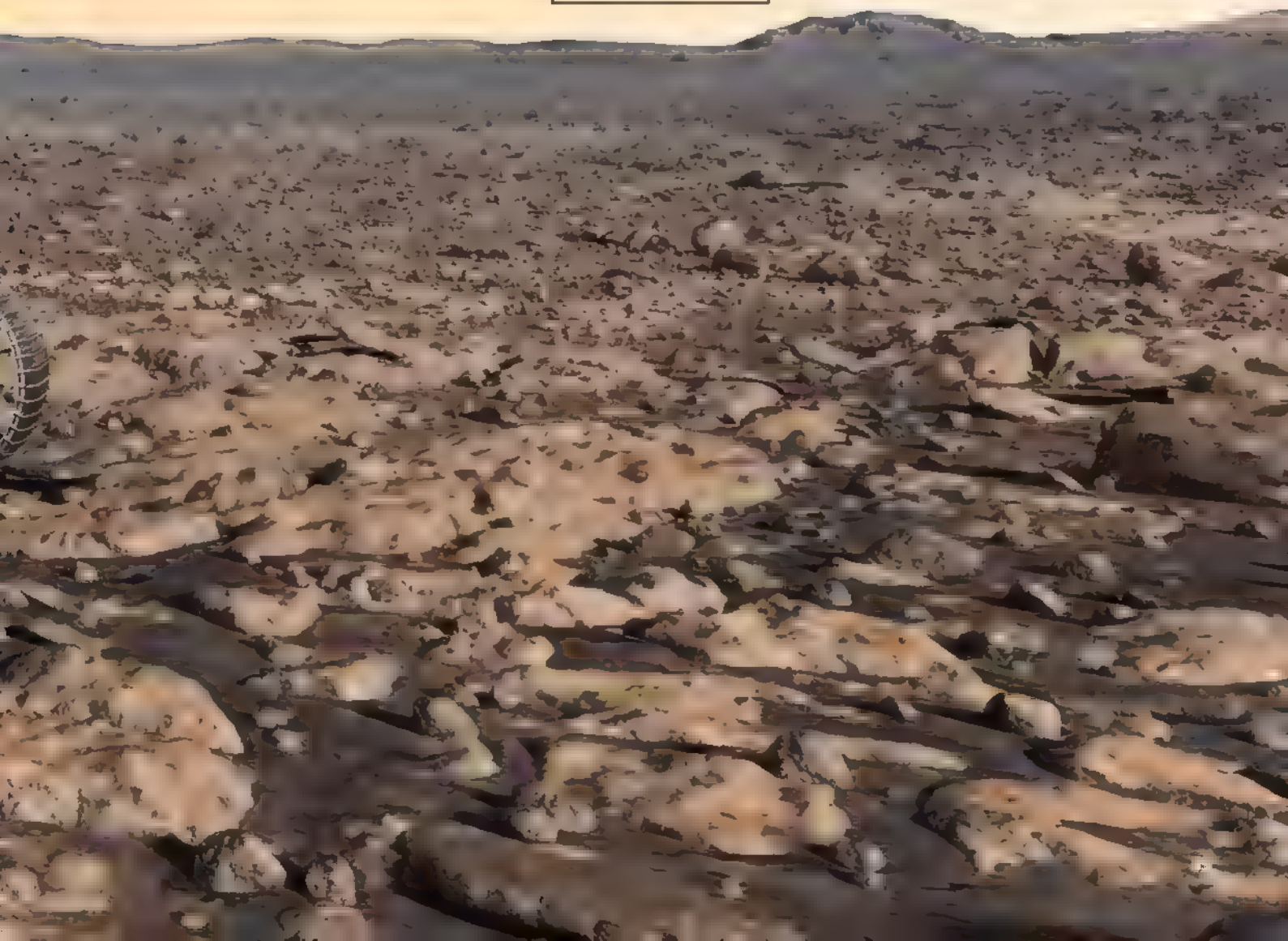


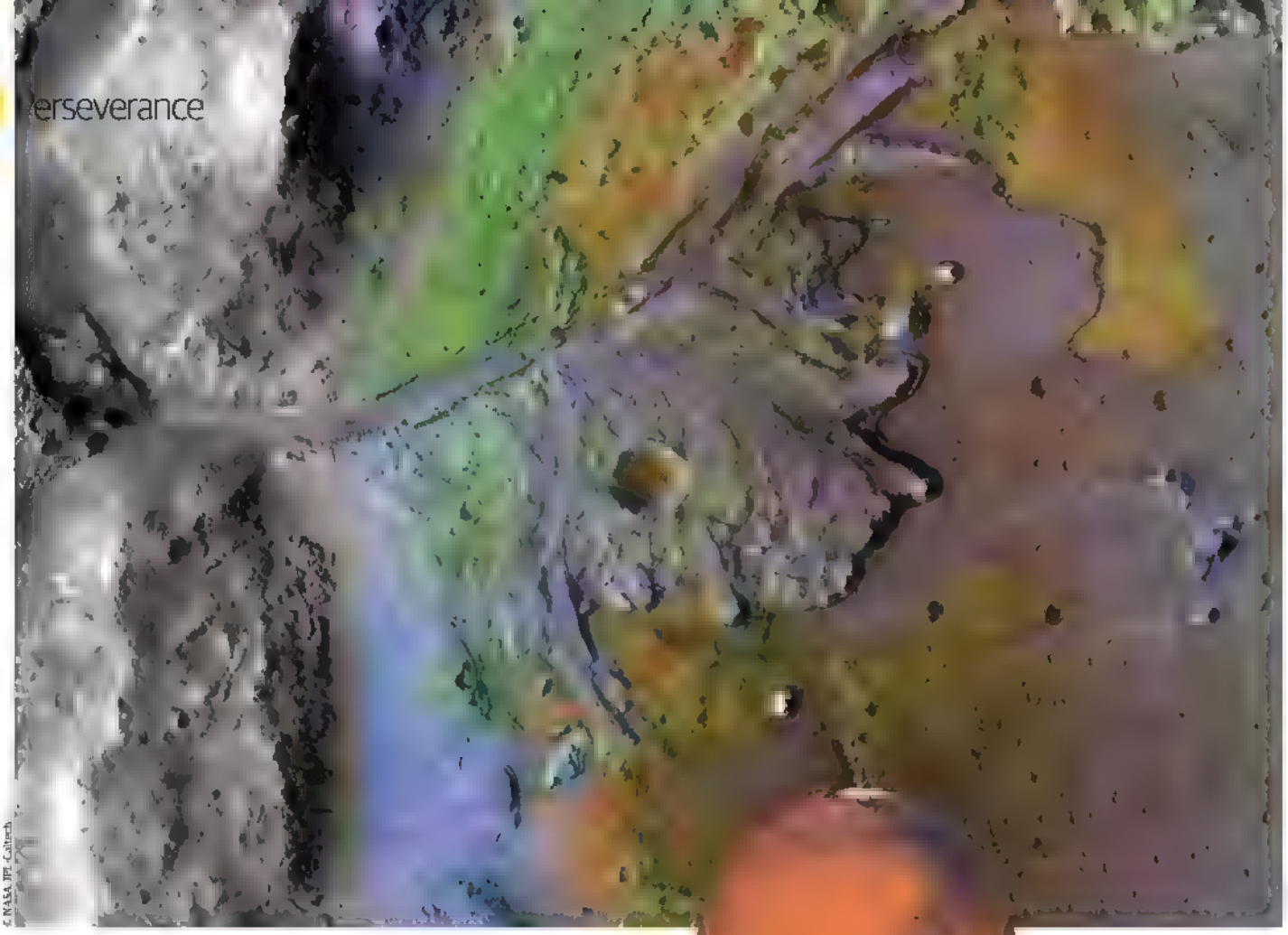
PREPARE FOR PERSEVERANCE

THE NEXT MARTIAN ROVER

Launched on 30 July, NASA's new craft will hunt for signs of past microbial life, cache rock and dig for soil samples – all while preparing for human exploration of the Red Planet

Reported by Lee Cavendish





© NASA JPL-Caltech

Meet the new Martian rover from NASA, Perseverance. This next-generation explorer was built upon the successes of its predecessors Spirit, Opportunity and the Mars Science Laboratory (MSL), also known as Curiosity. All of these robot explorers have worked towards helping us better understand the planet next door, Mars, and in the wider scope of science understanding the past biology and geology of other worlds. Now the Mars 2020 mission's Perseverance rover is looking to go even further.

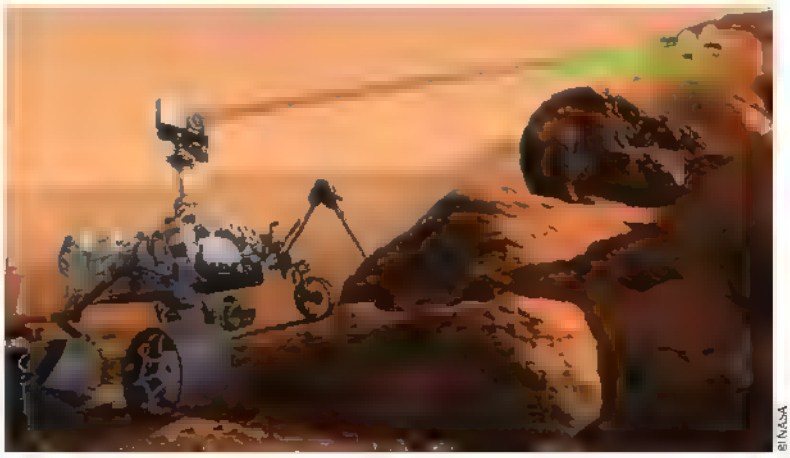
Perseverance was launched on 30 July 2020 carrying scientific equipment, cameras and microphones. It flew on top of an Atlas V 541 rocket, which also launched Curiosity and InSight, from Cape Canaveral Air Force Station in Florida. However, it wasn't travelling alone. Alongside Perseverance is a first-of-its-kind demonstration aircraft called the Mars Helicopter - more affectionately nicknamed Ingenuity. After their successful launch, the duo are currently spending over half a year voyaging through space to their destination, where the pair will hopefully land safely in Jezero crater on 18 February 2021. This is located on the western edge of Isidis Planitia, just north of the Martian equator.

After the much-fretted 'seven minutes of terror', where mission staff hold their breath for seven minutes as the rover goes through atmospheric entry, descent and landing, the rover will begin its primary mission duration of one Mars year - 687 days in Earth time. During this time Perseverance will inspect the Martian surface for signs of ancient life, characterise its geology and climate, prepare for future human exploration and collect samples of extraterrestrial rock for a future return mission.

"Perseverance is the most sophisticated and complex rover mission we've ever sent to Mars. Perseverance has a new and updated science payload that makes it better suited for searching for ancient signs of life in the rock record of Mars than any previous Mars mission," explains one of the Mars 2020 deputy project scientists, Dr Kathryn Stack Morgan.

"Previous rovers have scratched, brushed and drilled Mars rocks before, but Perseverance is the first rover that will collect and cache intact rock samples. Perseverance's sample caching system and sample tubes were designed to ensure the scientific integrity of these samples for a potential future return to Earth, and the mission has met unprecedented requirements for biological cleanliness and contamination control to accomplish this."

"One of Mars 2020's key objectives is to collect and cache a set of samples that could be returned



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Above: NASA's Mars Reconnaissance Orbiter has been watching over Jezero crater ahead of the rover's arrival

Right: The SuperCam will scrutinise the Red Planet's geology with unprecedented precision

to Earth by a set of future missions. This concept is called Mars Sample Return, and it has been a goal in the planetary science community for a very long time," explains Mars 2020's other deputy project scientist, Dr Ken Williford. "There are many scientific and technical reasons to return samples from Mars, but one of the most exciting is the opportunity to use our most powerful laboratories on Earth to look for evidence of past life."

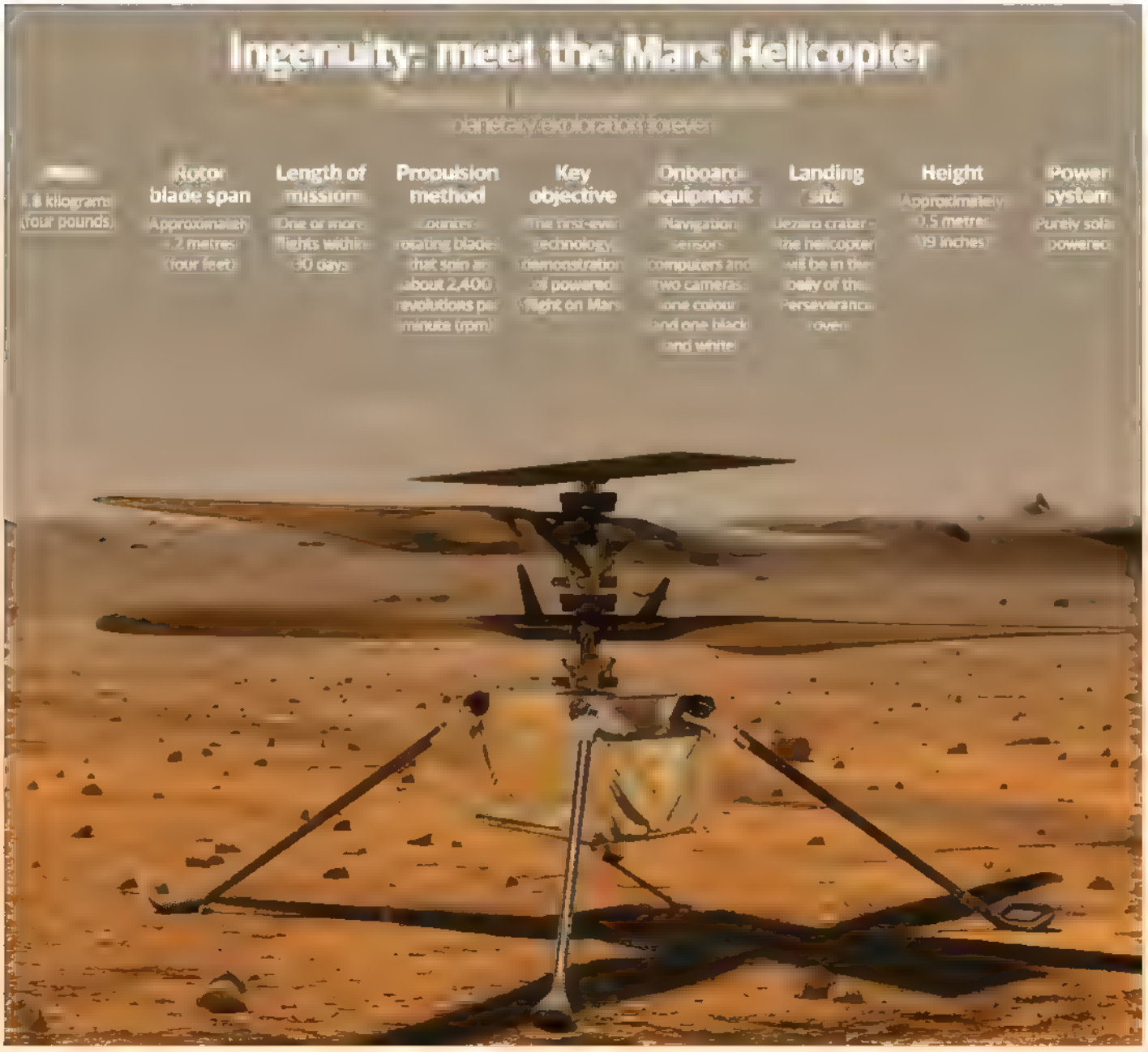
This innovation would not have been possible without the help of the missions that came before. The most obvious and recent example of this is Curiosity, and the two rovers share an almost-identical appearance. NASA has a habit of recycling space probe designs – for example, the currently operational InSight lander uses a design taken from the 2007 Phoenix lander. As the age-old saying goes: if it isn't broken, don't fix it.

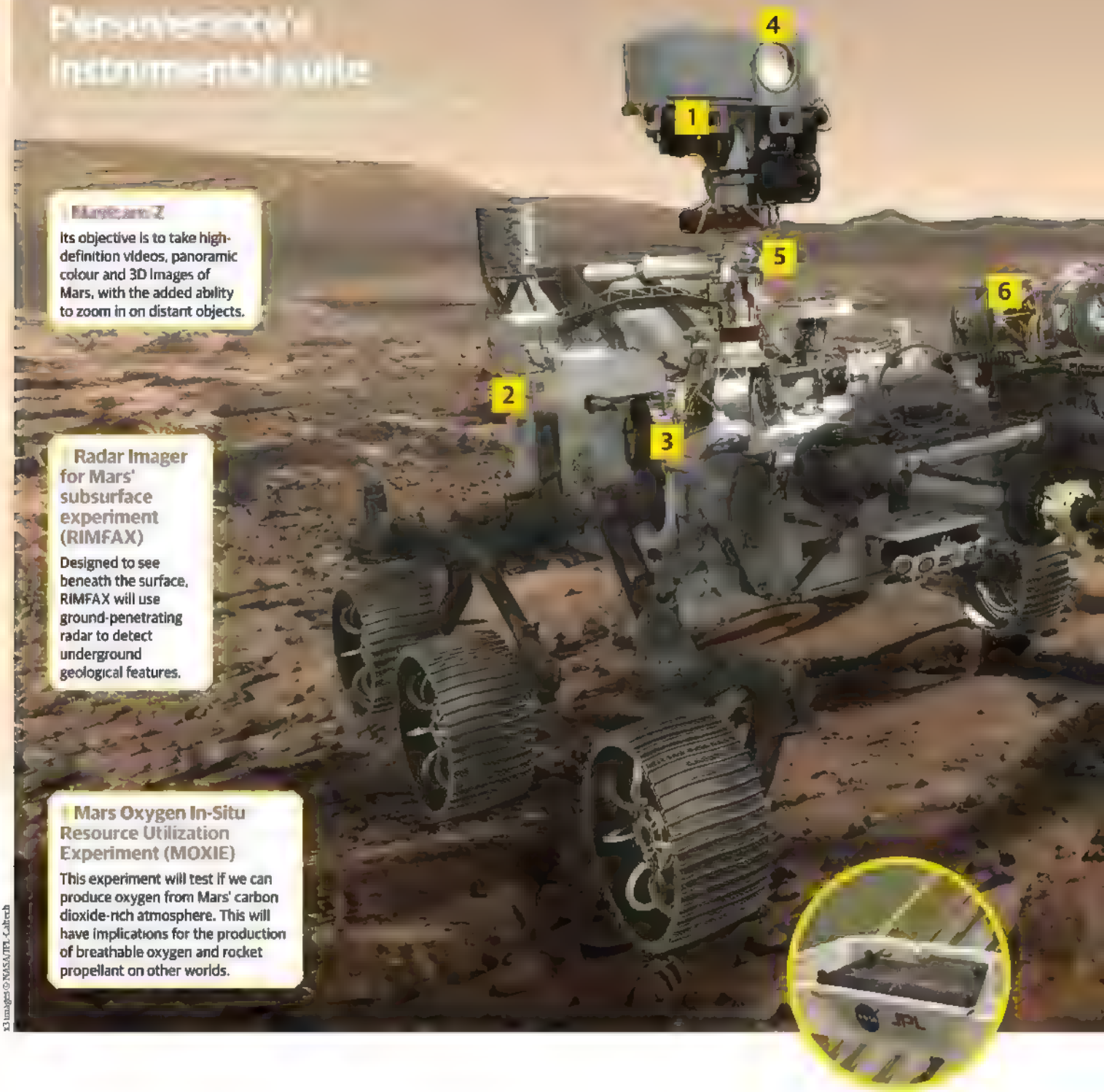
When asked what the visual differences are between Perseverance and Curiosity, Morgan replies: "Perseverance has redesigned thicker and sturdier wheels compared to Curiosity, with a different tread style, and it's one of the most obvious visual differences between the two. The Perseverance turret at the end of the rover's arm is also larger and heavier than Curiosity's turret."

It's possible for more invested admirers to spot the differences, but to the untrained eye the updates are hard to take notice of. Morgan explains the advantages of using an essentially identical layout: "The use of build-to-print designs from the Curiosity rover and its landing system allowed Mars 2020 to focus its resources on the mission's new elements and new technology."

Perseverance has a new and updated science payload compared to Curiosity. The Mastcam-Z and SuperCam instruments build on heritage from Curiosity's Mastcam and ChemCam instruments, but other Perseverance instruments – like PIXL and the SHERLOC spectrometer – are entirely new.

"PERSEVERANCE IS BETTER SUITED FOR SEARCHING FOR ANCIENT SIGNS OF LIFE THAN ANY PREVIOUS MARS MISSION" KA





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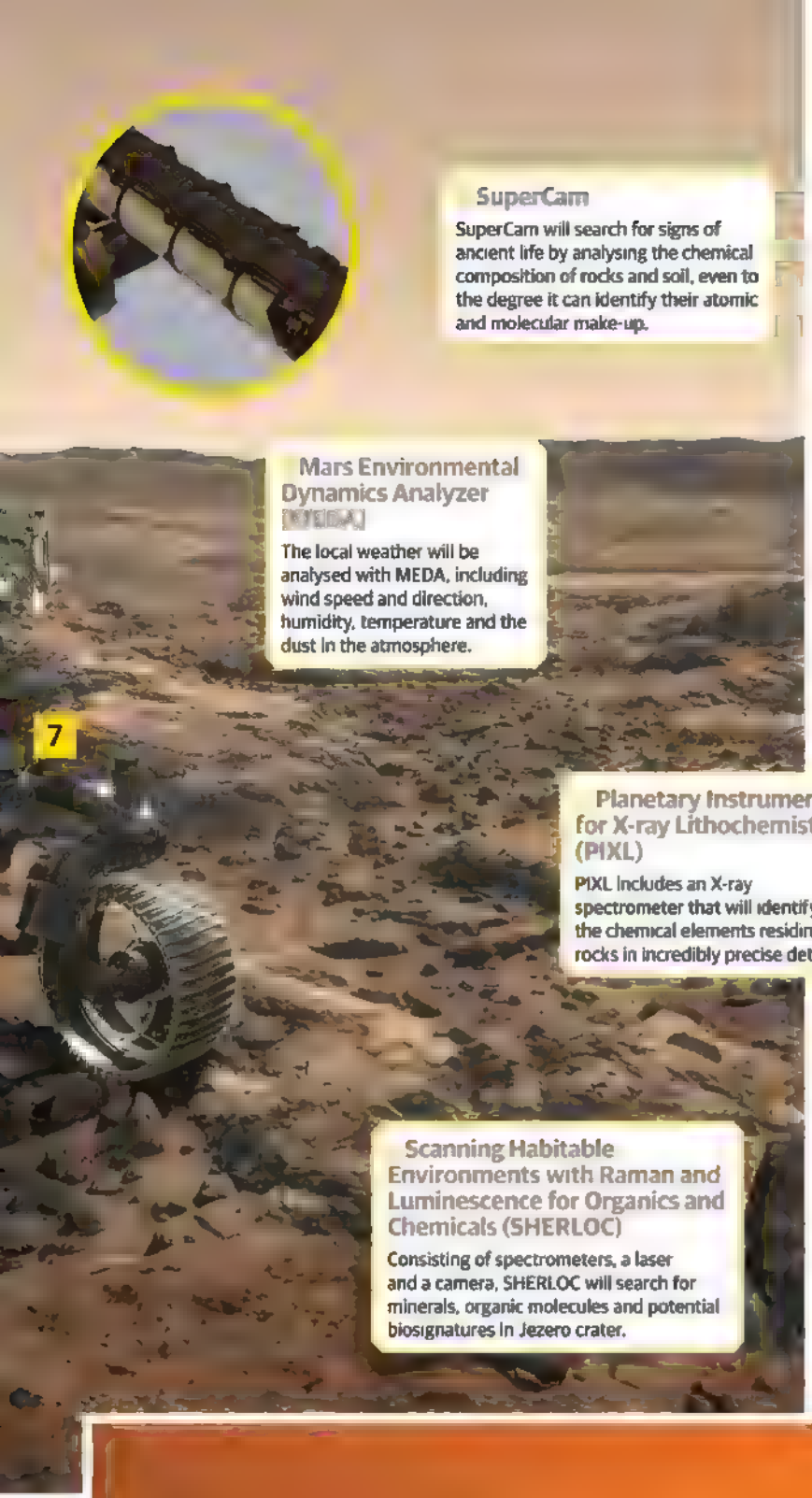
Curiosity measures chemistry, mineralogy and the organic content of rock samples in a 'bulk' way from powdered drill fines. In contrast, Perseverance's PIXL and SHERLOC instruments allow us to produce detailed maps of chemistry, mineralogy organics and texture without grinding up the rocks."

Seven new scientific instruments – including the aforementioned Planetary Instrument for X-ray Lithochemistry (PIXL), Scanning Habitable Environments with Raman and Luminescence for Organics and Chemicals (SHERLOC) spectrometer, SuperCam and Mastcam-Z – will explore the geology of the Jezero crater landing site, assess its history of water and habitability, search for signs of past life and snap some more of those Mars selfies that everybody loves so much.

One experiment that will contribute to the Mars 2020 project, but will separate from the rover on arrival, is the Mars Helicopter. In April 2020 it was named 'Ingenuity' by a student from Tuscaloosa County High School in Northport, Alabama. It's purely a demonstration experiment. It is intended to become the first aircraft to execute powered flight on another planet, and if it works it will be a truly remarkable feat of engineering. Ingenuity will inform future innovative missions about flight on Mars, where the gravity is roughly a third of the strength of Earth's. The atmospheric density at Mars' surface level is just one per cent of Earth's at sea level, so there have always been questions about how these alien conditions on Mars will alter aircraft flight performance.

"Rather than supporting Perseverance's science mission, the helicopter is meant to pave the way for future Mars exploration. Perseverance's cameras will be important to select a safe launch and landing area for the helicopter," says Williford. "If all goes well, we should be able to capture an exciting image of the helicopter in flight!"



SuperCam

SuperCam will search for signs of ancient life by analysing the chemical composition of rocks and soil, even to the degree it can identify their atomic and molecular make-up.

Mars Environmental Dynamics Analyzer (MEDA)

The local weather will be analysed with MEDA, including wind speed and direction, humidity, temperature and the dust in the atmosphere.

Planetary Instrument for X-ray Lithochemistry (PIXL)

PIXL includes an X-ray spectrometer that will identify the chemical elements residing in rocks in incredibly precise detail.

Scanning Habitable Environments with Raman and Luminescence for Organics and Chemicals (SHERLOC)

Consisting of spectrometers, a laser and a camera, SHERLOC will search for minerals, organic molecules and potential biosignatures in Jezero crater.

Below: Perseverance's MOXIE and MEDA instruments will return valuable data for the future human exploration of Mars

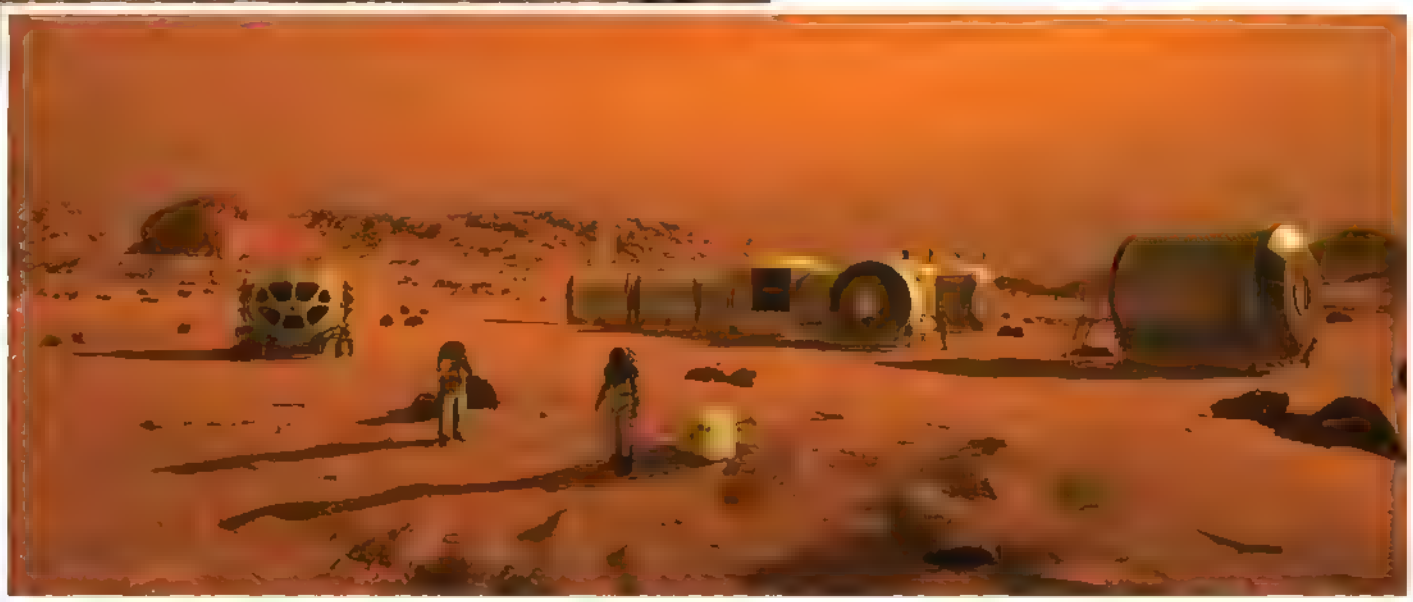
With this outstanding arsenal of investigative apparatus the Mars 2020 mission will be well equipped to reveal the secrets of Jezero crater. But why this Martian site in particular?

"Jezero crater was chosen as the landing site for the Perseverance rover because it contains evidence of an ancient lake and delta that we believe was once habitable," says Morgan. "Delta and lake sediments on Earth are known to be great preservers of organic matter and evidence of life and we hope that signs of ancient Martian life may be preserved in the rocks exposed in Jezero crater."

When looking back at the Mars Exploration Rovers, Spirit and Opportunity, and reminiscing about their journeys through Gusev crater and Meridiani Planum respectively, they both followed the water. Their main objective was to determine whether Mars was once a wet planet or not. Together they contributed pivotal evidence to the popular hypothesis that Mars had oceans, lakes and a warmer atmosphere over 3 billion years ago. A host of rovers and orbiters were fundamental in coming to this conclusion. The European Space Agency's Mars Express orbiter and NASA's Mars Reconnaissance Orbiter have even suggested water ice still exists at the planet's poles.

Now the Mars 2020 Perseverance rover is able to build upon this amazing legacy of discovery and focus on whether there was ever ancient life on Mars. It is generally agreed that a warm and wet planet is ideal for life as we know it to arise - which

"RATHER THAN SUPPORTING PERSEVERANCE, THE HELICOPTER IS MEANT TO PAVE THE WAY FOR FUTURE MARS EXPLORATION" KEN



Mars once was. With Jezero crater as a former lake and delta, being an excellent candidate to scrutinise, scientists may finally be able to answer the all-important question of whether there has ever been life elsewhere in the Solar System.

"If we see chemical elements, minerals and organic molecules that tend to be associated with life, and especially if we see these things arranged in spatial patterns that suggest biology, this could be evidence of ancient life on Mars," says Williford.

It could be the case that in the near future humans will be walking around on Mars. NASA and other global space agencies and private companies are currently looking to visit, inhabit and colonise the Red Planet. Although this will all happen in small stages over the next few decades, it is NASA's current intention to go back to the Moon by 2024 and then onward to Mars. Perseverance will assist in this dream of interplanetary exploration.

As Williford explains, Mars 2020 "has a weather station called MEDA that is contributed by Spain and will improve our understanding of surface conditions that astronauts would experience. We have an instrument called MOXIE that takes in carbon dioxide from the Martian atmosphere and converts it to oxygen."

As seen with previous NASA missions, the public have once again been able to register to become a part of this endeavour. Similar to the space agency's past InSight and Parker Solar Probe mission launches, NASA created the 'Send Your Name To Mars' campaign, which has resulted in 10,932,295 people having their names stencilled onto three fingernail-sized silicon chips by electron beams. These three chips were attached to an anodised plate which also had a laser-etched graphic depicting Earth and Mars on either side of the Sun as it shines on both planets - akin to some depictions of the Golden Records sent aboard NASA's Voyager space probes. This remarkable rover bears the expectations of over 10 million people on its robotic shoulders, but if its predecessors are anything to go by, this mission will reap some groundbreaking results for many Earth years to come and will pioneer future missions to even greater heights.

"ONE OF MARS 2020'S KEY OBJECTIVES IS TO COLLECT AND CACHE A SET OF SAMPLES THAT COULD BE RETURNED TO EARTH"

5 engineering facts as told by the team

Dr Kathryn Stock Morgan

Dr Ken Williford

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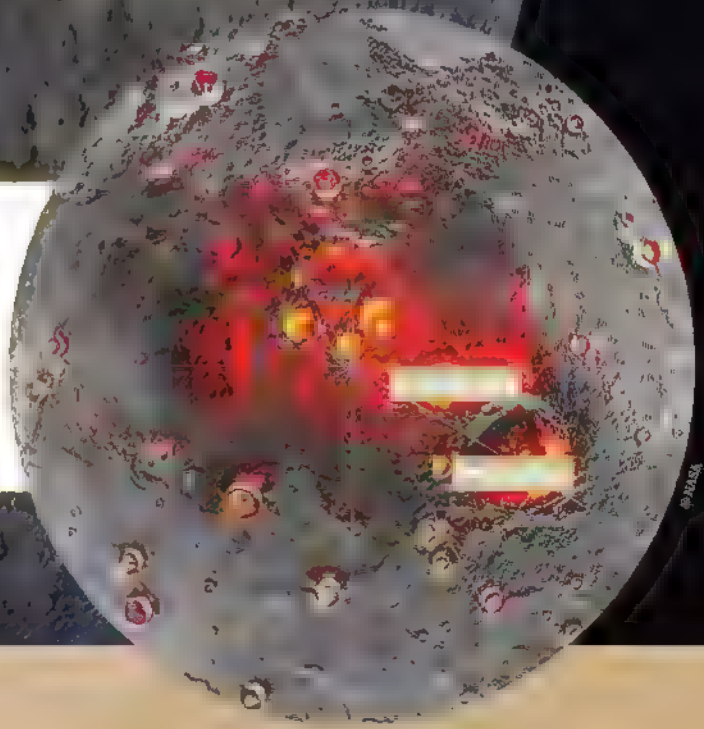
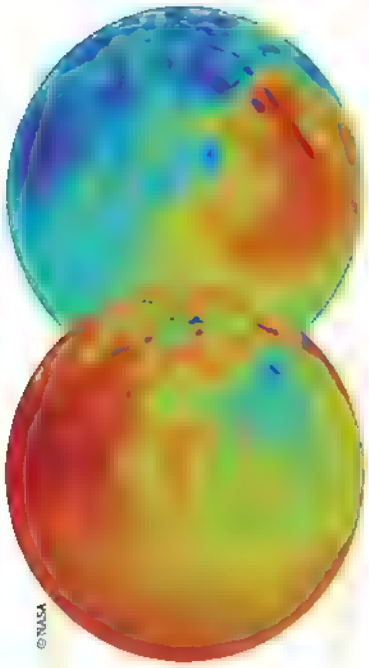
WHAT'S NEW AT MERCURY?

Scientists are still busy analysing data from the MESSENGER mission and it has plenty of surprises



ICE ON A HOT PLANET

A view of the area around Mercury's north pole, with regions that permanently lie in shadow shown in red and suspected traces of ice shown in yellow.



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ELEMENTS THAT 'SHOULDN'T BE THERE'

▲ MESSENGER's instruments included spectrometers to analyse the chemical composition of Mercury's surface – they discovered a surprisingly high level of volatile elements such as sulphur and potassium.

Which planet is Earth's nearest neighbour in the Solar System? The obvious answer is Venus, which makes the closest approach to us but it spends half its orbit on the other side of the Sun, when it's further away from us than Mercury. It was only last year that Tom Stockman, a graduate research assistant at Los Alamos National Laboratory, New Mexico, and colleagues crunched the numbers to work out which planet is actually closest on average – and they were as surprised as anyone by the answer. "When averaged over time, Earth's nearest neighbour is in fact Mercury," they wrote.

Despite its proximity, Mercury has always been a mysterious planet due to the difficulty of observing it through Earth-based telescopes. That's down to a combination of its small size and the fact that it never gets very far from the Sun in the sky. The only time it makes a really spectacular sight, in fact, is when it passes directly in front of the Sun during a transit of Mercury – like the one that took place last year in November 2019.

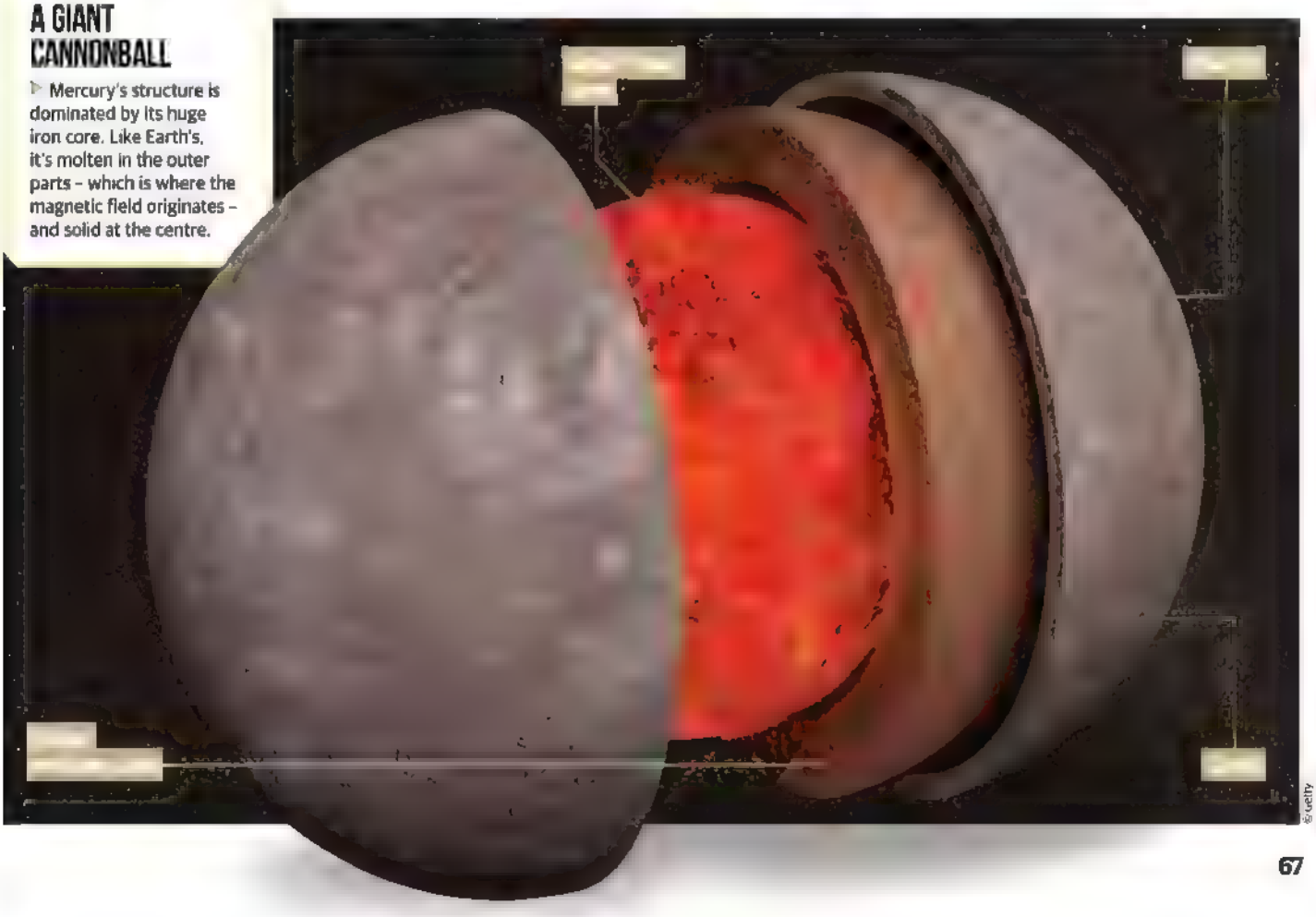
If Mercury is a difficult planet to observe from Earth, it's not an easy destination for spacecraft either. That's partly because a spacecraft speeds up under the effect of gravity as it falls towards the Sun – and then its rocket engine has to work hard to lose that excess speed when it gets to Mercury. Another problem is the extreme heat – well over 400 degrees Celsius (752 degrees Fahrenheit) – in the vicinity of Mercury, which poses serious challenges for spacecraft designers. Since the dawn of the space age, only two space probes have been to Mercury – Mariner 10 in the 1970s, followed by MESSENGER more recently, both by NASA.

The photographs sent back by Mariner 10, which made three close passes of Mercury in 1974 and 1975, revealed a desolate, crater-studded landscape that looks a lot like our Moon. But the mission had a surprise for scientists in its discovery of a well-defined magnetic field around the planet. It's a hundred times weaker than Earth's field, but Venus and Mars don't have internal magnetic fields at all, and Mercury wasn't expected to either.

A closer look at Mercury's magnetic field was one of the key objectives of NASA's follow-up mission, MESSENGER, which entered orbit around the planet in March 2011. It remained there until it ran out of manoeuvring propellant four years later – and in the final few months the mission controllers got increasingly bold. They dipped the spacecraft to just 15 kilometres (9.3 miles) above the planet, allowing them to measure relic magnetism in the surface rocks. "The signals we detected are really small, and very hard to measure," explains planetary geophysicist Catherine Johnson. "We'd never have been able to measure them if not for these really

A GIANT CANNONBALL

▶ Mercury's structure is dominated by its huge iron core. Like Earth's, it's molten in the outer parts – which is where the magnetic field originates – and solid at the centre.



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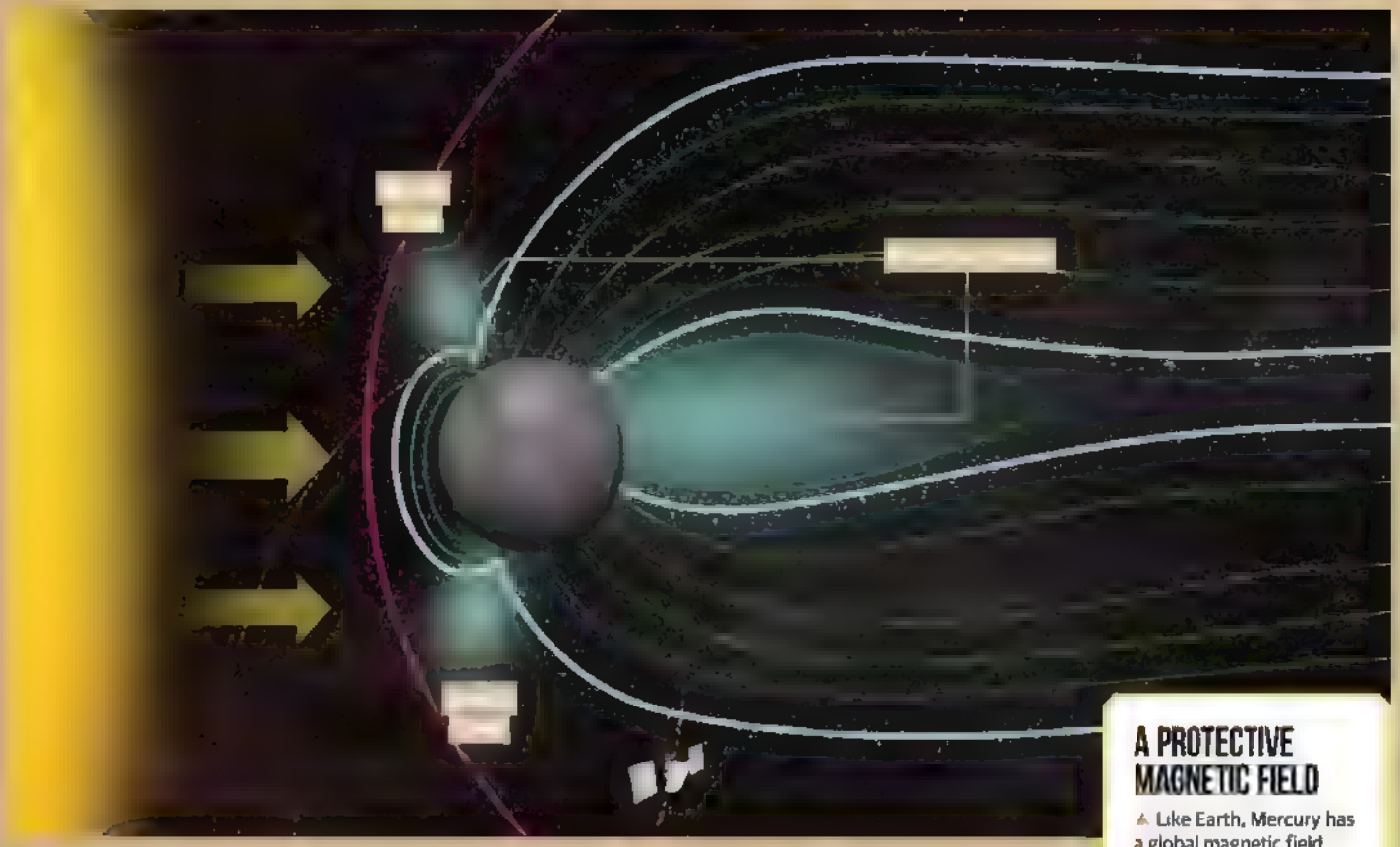
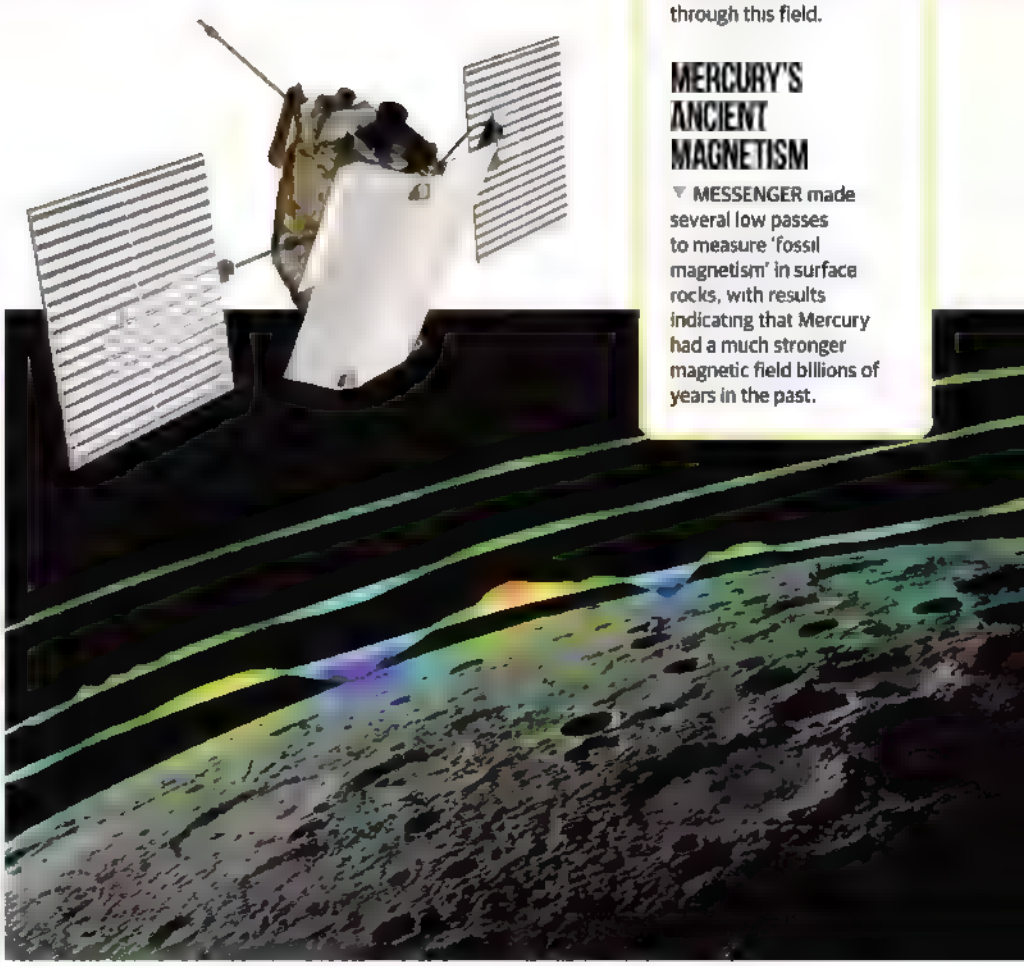


A PROTECTIVE MAGNETIC FIELD

▲ Like Earth, Mercury has a global magnetic field which helps to shield it from the solar wind. The dashed red line shows MESSENGER's orbit through this field.

MERCURY'S ANCIENT MAGNETISM

▼ MESSENGER made several low passes to measure 'fossil magnetism' in surface rocks, with results indicating that Mercury had a much stronger magnetic field billions of years in the past.



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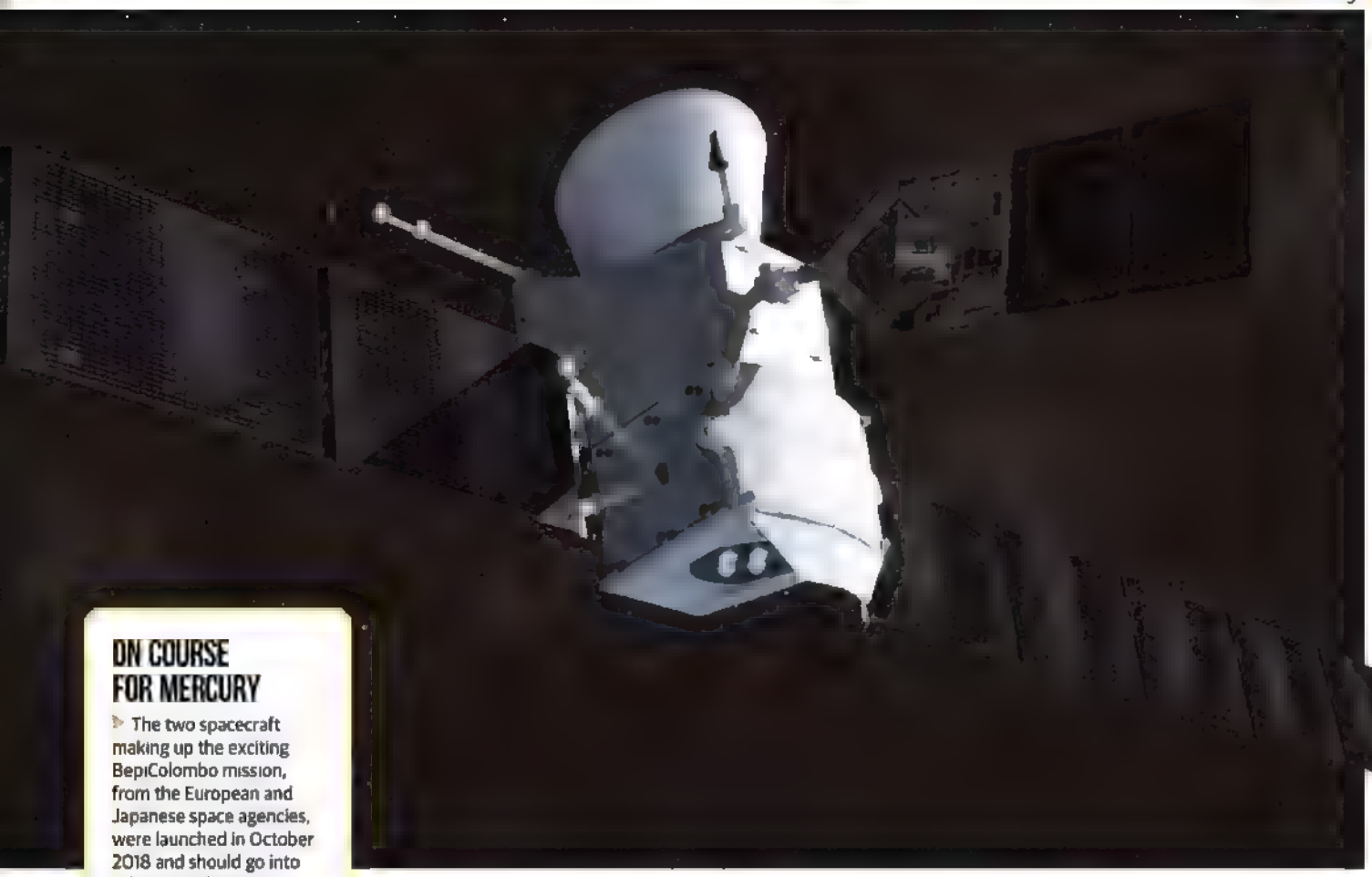
"WE'D NEVER HAVE BEEN ABLE TO MEASURE THEM IF NOT FOR THESE REALLY RISKY LOW-ALTITUDE OBSERVATIONS"

risky low-altitude observations in the last few months of the MESSENGER mission."

The measurements indicated that not only is Mercury's magnetism very old – going back at least 3.8 billion years – but it was much stronger in the past, "comparable to the strength of Earth's magnetic field today," according to Johnson.

When all its propellant was used up, MESSENGER was deliberately crashed into Mercury's surface – the first Earth-made artefact on the planet – on 30 April 2015. From NASA's point of view the mission was a huge success, repeatedly surprising researchers with its discoveries. "In the end, most of what we considered to be gospel about Mercury turned out to be a little different than we thought," as mission scientist William McClintock said at the time.

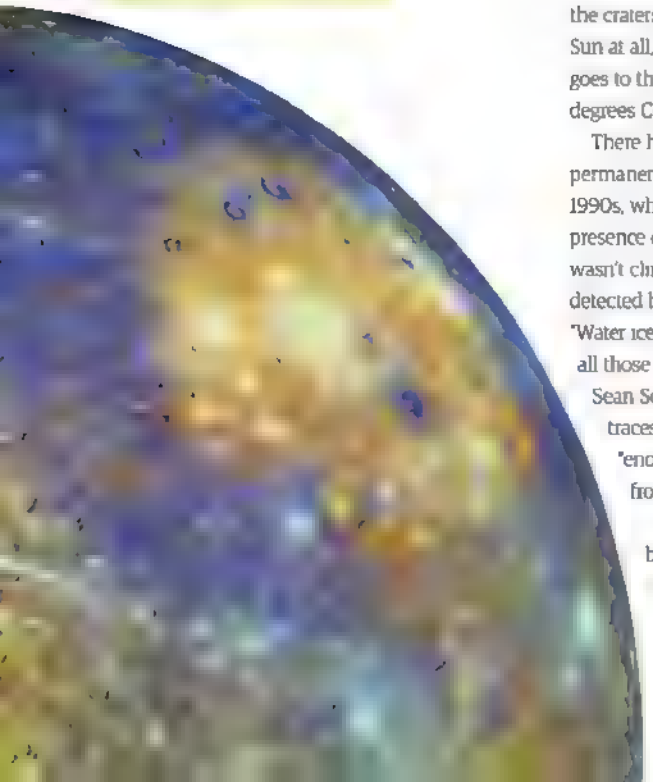


ON COURSE FOR MERCURY

The two spacecraft making up the exciting BepiColombo mission, from the European and Japanese space agencies, were launched in October 2018 and should go into orbit around Mercury in late 2025.

RETHINKING MERCURY'S ORIGIN

It used to be thought that Mercury suffered a huge impact which stripped off its outer layers, but that's less likely now we know there are volatiles on the surface.



"MOST OF WHAT WE CONSIDERED TO BE GOSPEL ABOUT MERCURY TURNED OUT TO BE A LITTLE DIFFERENT THAN WE THOUGHT"

Among MESSENGER's biggest surprises was the discovery of water ice on Mercury. This seems odd, given the extremely high surface temperatures in direct sunlight. But there are spots inside some of the craters near the planet's poles that never see the Sun at all, and consequently the temperature there goes to the opposite extreme - closer to minus 200 degrees Celsius (minus 328 degrees Fahrenheit).

There had been hints of ice inside these permanently shadowed craters as long ago as the 1990s, when radar measurements indicated the presence of highly reflective material. The issue wasn't clinched, however, until MESSENGER detected hydrogen atoms in the same locations. "Water ice is the only candidate we've got that fits all those observations," as principal investigator Sean Solomon explained. It's not just a few traces of ice, either - according to Solomon it's "enough ice to encase Washington DC in a frozen block two-and-a-half miles deep".

Another unexpected finding was a brand-new type of surface feature that isn't seen anywhere else in the Solar System except Mercury. Called 'hollows', these are shallow depressions found inside many of the planet's craters. They're believed to have formed when volatile components in the surface material evaporated, causing the remaining material to collapse. "The hollows are one of the most viscerally interesting discoveries from the mission," according to another MESSENGER scientist, Steve Hauck. "They were completely unexpected – a new landform, and one that appears to form by loss of rock to space."

The idea that volatile materials boiled off Mercury in the distant past seems reasonable enough, given its hot location close to the Sun. What would be more surprising would be to find volatile materials still on the planet's surface today – and yet that's exactly what MESSENGER did find. It's a subject Brian Cox talked about in his TV series *The Planets* last year. "The discovery of relatively large concentrations of elements like sulphur and potassium on Mercury's surface was a huge surprise," he said. "So Mercury is an enigma, and discoveries like these force us to completely


MERCURY
MASS
330,104,000,000,000
EQUATORIAL DIAMETER
4,879
ORBIT DISTANCE
57,909,227
VENUS
MASS
4,867,320,000,000,000
EQUATORIAL DIAMETER
12,104
ORBIT DISTANCE
108,209,475
EARTH
MASS
5,972,190,000,000,000
EQUATORIAL DIAMETER
12,742
ORBIT DISTANCE
149,598,262
INNER PLANETS
How does the third rock from the Sun compare to those further in?
© Adrian Mann
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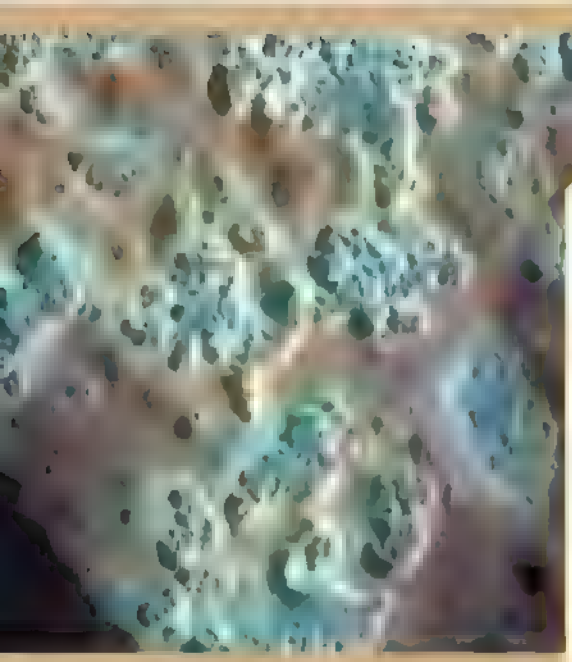
rethink our theories about the formation of the planet."

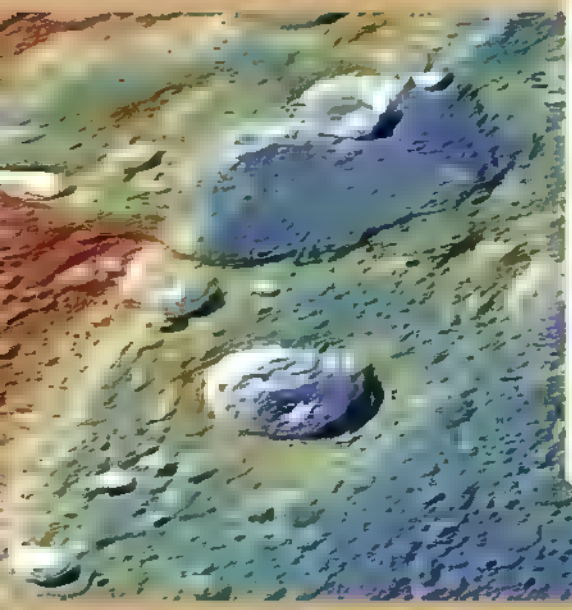
The problem with this new discovery was that it didn't fit in with existing ideas about Mercury's origin, which had been developed over the years to explain its unusual internal structure. Like Earth, the planet is made up of a rocky crust and mantle surrounding an iron-rich core - but in Mercury's case the core is huge, making up almost 85 per cent of its volume. For a long time it was assumed that Mercury must have started out looking very similar to Earth in size and composition. Then, billions of years ago, it had its outer layers knocked off in a collision with a huge asteroid.

The problem with that theory is it doesn't explain why there's so much sulphur and potassium on Mercury's surface today. It now seems likely that Mercury formed much as it is now, and that its large core was a consequence of the different physical conditions in the inner parts of the early Solar System compared with further out where the other planets formed. That's supported by the discovery of exoplanets orbiting close to other Sun-like stars, which also appear to have large metallic cores like Mercury.

Despite its numerous discoveries, MESSENGER left plenty of unanswered questions - but fortunately there's another mission, BepiColombo, on its way to Mercury right now. Made up of two separate spacecraft, the ESA's Mercury Planetary Orbiter and the Japan Aerospace Exploration Agency's Mercury Magnetospheric Orbiter, it's due to arrive in 2025. With 16 scientific instruments, researchers are hoping BepiColombo will make just as many discoveries as MESSENGER did.

"THE DISCOVERY OF RELATIVELY LARGE CONCENTRATIONS OF ELEMENTS LIKE SULPHUR AND POTASSIUM ON MERCURY'S SURFACE WAS A HUGE SURPRISE"





A NEW TYPE OF FEATURE

These rounded depressions in Raditladi Basin are examples of 'hollows' – features unique to Mercury which may have been formed when volatile materials evaporated into space long ago.

MERCURY ON STEROIDS?

That's how NASA described exoplanet K2-229b, which resembles Mercury in being iron-rich and orbiting close to a Sun-like star, but it's four-times bigger and, at 2,000°C (3,632°F), much hotter.

THE SHRINKING PLANET

As Mercury's interior has cooled down, the planet has shrunk, creating tectonic fault lines such as the one pictured here, Carnegie Rupes.

INTERVIEW BIO

Dr Nour Raouafi

Raouafi is a Tunisian astrophysicist at Johns Hopkins University's Applied Physics Laboratory (APL) in Maryland and the project scientist for NASA's Parker Solar Probe mission. He is an expert in many solar and heliospheric topics, including solar magnetic fields, coronal plumes and jets, coronal mass ejections (CMEs), solar wind, solar energetic particles and many other areas.

For the last two years the Parker Solar Probe has been beaming back unique data sets while breaking records when it comes to how close a human-made object has been to the Sun and how fast it travels. Its latest encounter reached within 18.7 million kilometres (11.6 million miles) of the Sun and sped past at 393,000 kilometres (244,225 miles) per hour.

PARKER SOLAR PROBE: TWO YEARS ON

"THIS COMING DECADE WILL BE THE GOLDEN AGE OF SOLAR AND HELIOPHYSICS RESEARCH"

All About Space catches up with the project scientist for NASA's incredible Parker Solar Probe mission, Dr Nour Raouafi - a spacecraft continuously breaking records and surpassing all expectations as it orbits the Sun

Interviewed by Lee Cavendish

How's the Parker Solar Probe doing? Are there any updates that we should be aware of?

The Parker Solar Probe is doing great. We are going through our fifth encounter and recently we were the closest we've ever been to the Sun. After a period of five days where we could not communicate with the spacecraft, it sent us a signal that it's healthy and it's doing what it's supposed to do. In terms of science, it's just amazing. Whenever the spacecraft gets closer to the Sun, we are learning new things that we've never seen before.

What is the major mystery surrounding the Sun and its corona that astronomers are desperately trying to solve, and are hoping the Parker Solar Probe will help shed light on?

There are a few phenomena that were discovered decades ago, but we are still struggling to understand. I think the one that is most puzzling is what we call the 'coronal heating problem'. The corona, which is the outermost layer of the solar atmosphere, is 300 times hotter than the solar surface. And we know that all the energy is coming from inside the Sun, so in a way it's counter-intuitive that the source is cooler than the environment around it. But the Parker Solar Probe is giving us clues and hints as to what might be causing excess heating there.

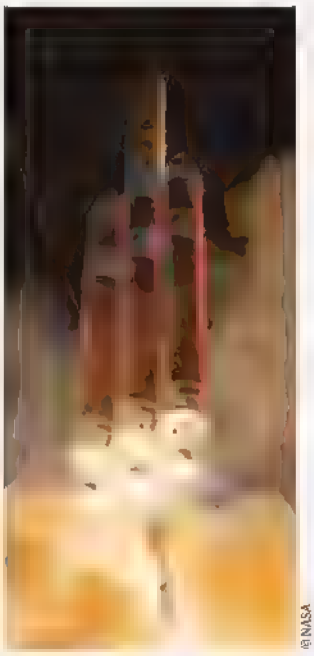
Another phenomenon, which is very closely related to coronal heating as well, is what we call the acceleration of solar wind. The solar wind is a flow of charged particles - electrons, protons, ionised helium and heavy elements - that are constantly flowing away from the Sun to the rest of the Solar System. The issue with the solar wind is that low down [within the solar atmosphere] these particles are flowing at very slow speeds, but they get accelerated to hundreds of kilometres per second in a very short distance. We don't know exactly what is the physical mechanism that gives them the energy to accelerate to these high speeds.

The third phenomenon, and we are impacted by it every day, is big explosions on the Sun. Whenever there is a flare or a coronal mass ejection (CME) erupting on the Sun, there is a population of particles that get accelerated to almost the speed of light. We call them solar energetic particles.

The Parker Solar Probe was built specifically to be able to shield its instruments in a really dangerous environment. How has its heat shield been constructed so that it can withstand such dangerous temperatures and radiation while remaining relatively lightweight?

The heat shield is basically made of carbon foam. Most of it is a vacuum. It's like a sponge made out of carbon that is sandwiched between two sheets, which are also compressed carbon. The other thing that is specific to the Parker Solar Probe is a plasma spray that is white and is on top of the heat shield. The goal here is to reflect as much light from the Sun as possible.

When we are closest to the Sun in 2024, that side of the heat shield will be more than 2,500 degrees Fahrenheit [1,371 degrees Celsius]. 4.5 inches (11.5 centimetres) inward, which is the other side of the heat shield, will be at almost 700 degrees Fahrenheit [371 degrees Celsius], so there we have already lost a lot of heat. And from that backside of the heat shield to the bus, where the instruments are mounted, it is at room temperature.



Right: The closest-ever approach to the Sun planned for the Parker Solar Probe will occur in 2024.

What impacts can space weather and solar wind have to us on Earth?

Let me start by saying, we are now starting to think about sending women and men to the Moon, and maybe to Mars in the near future. If we are going to do that, we need to protect these people out there. We cannot just launch them out there. If we don't protect them sufficiently, these solar energetic particles will not be good for them and also for the space equipment. It will have a different impact on our environment here on Earth and also the other planets as well.

Just as a simple example: we rely a lot on GPS which is functional because we have spacecraft orbiting Earth. And if there is a big explosion on the Sun and it burns some of these satellites out, some of us will be in trouble because GPS will not be working anymore.

Another example is if we have a huge CME or flare that will cause a humongous geomagnetic storm here on Earth - that can cause a shutdown of power grids. That will be devastating for the economy and for the societal fabric. That's actually why space weather is a big topic now for research and for all of us here.

It's been two years now since the Parker Solar Probe was launched. Do you have any favourite moments or a favourite result that has come from the mission so far?

A lot of them. One of my favourite moments - I may not have enjoyed it when it happened, but now with hindsight I enjoyed it a lot - was the launch of the mission. I mean, we have been waiting for the Parker Solar Probe for 60 years, and on 12 August 2018 we put it on top of the most powerful rocket in existence, and all you hope for is that everything goes smoothly. I was so stressed when I was watching it, and it all went really well.

But after that, what we have discovered is something amazing. The spacecraft we designed at APL is functioning way better than we had thought it would. What we are getting back from this machine is amazing. Let me give you an example in terms of science data: we are bringing three to four times the volumes we thought we would do pre-launch. We also thought pre-launch that we were only going to operate instruments when we were close to the Sun and after launch. We are now basically operating the instruments almost all of the time.

The planned mission duration is currently seven years. Do you think it could possibly reach ten years or more?

If by the end of the seven years, if everything is going well, it's a no-brainer that we will request an extension of the mission. During these seven years we will have basically covered half of the solar cycle. We launched at the minimum, and by 2025 we will be at the maximum of the solar cycle. What I want to see from the Parker Solar Probe is to basically complete a whole cycle, going from the maximum to the other minimum - which is an extension of the mission by five to six years. I would love to see that.

Could this information be used for stars beyond our Solar System as well?

That's a very good remark. By understanding how the Sun works, we can actually project all we gain from what we learned about the Sun to other stellar systems. Other stellar systems are so far away that we cannot study them in detail as we are currently doing with the Sun. What we learn from the Parker Solar Probe, by explaining all these big phenomena we talked about at the beginning, we can basically take that and project it onto other stellar systems and why would you want to do that?

It's because we are so curious about whether there are other planets out there and whether there is habitability around other stars. The interaction between the stars and the planets is so crucial for life and for habitability. By understanding how the Sun behaves and how it interacts with us here on Earth and other planets, it will help us tremendously in understanding other stellar systems. In a way the Parker Solar Probe is our ambassador to other stellar systems as well - as it will help us understand other stellar systems.

Top: The heat shield is an integral part of the spacecraft and keeps the instruments at room temperature

Right: Solar Orbiter's Extreme Ultraviolet Imager (EUI) has recently revealed omnipresent tiny solar flares, now referred to as 'campfires'

In December 2019 news came out around the Parker Solar Probe regarding the release of the first year of scientific results. Could you explain some of the main news stories that came out after this first year?

That was really an ideal time for the Parker team, but also for everybody. For humanity. Flying a spacecraft around this star is something very challenging. In terms of science, it was amazing. But before going into this, let me say this. You will have to wait a little bit, probably a few months, and you will be seeing another wave of big discoveries from the Parker Solar Probe. We just got the new data from orbit four, which is the closest perihelion to the Sun, and we are seeing new things that we have not seen before.

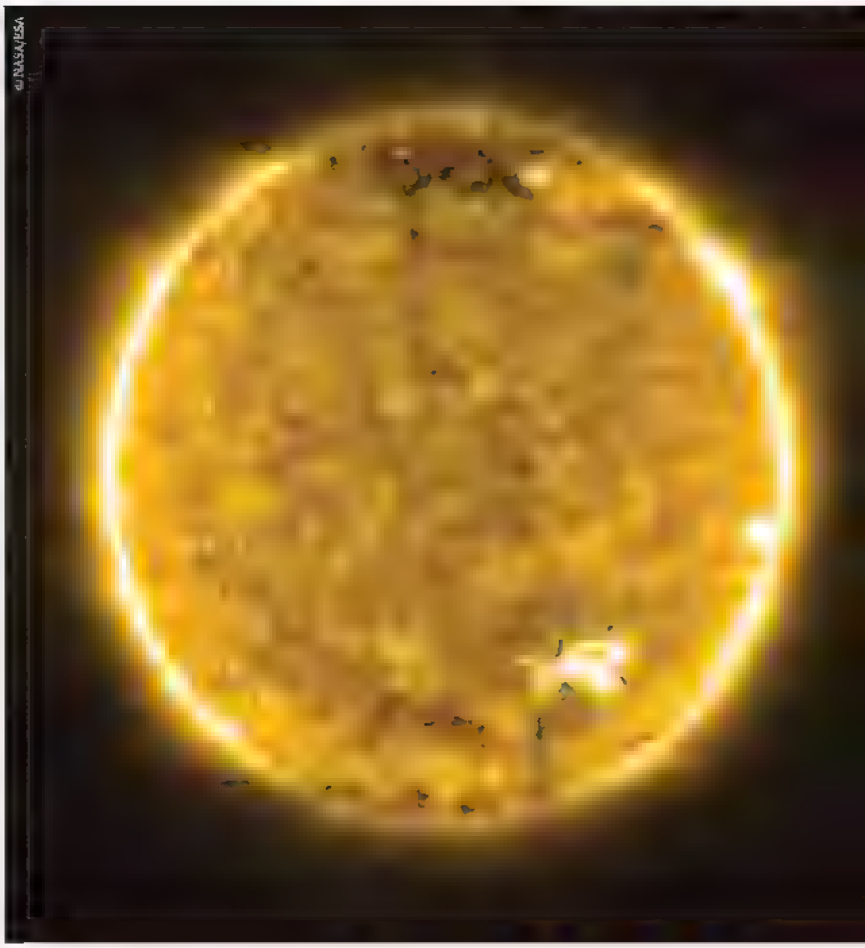
Going back to what we released in December and later on in February in a special issue in the *Astrophysical Journal*, there are a key number of discoveries that are breakthrough discoveries. One of them is what we call the 'dust-free zone'.

When you look at the heliosphere, there is dust almost everywhere. The dust comes from asteroids and comets that grind up in the Solar System, but the closer the dust particles get to the Sun, the smaller they get. At a certain point they will evaporate. The result of that is you create a zone around the Sun where there is no dust. This was hypothesised in 1929, and since then people have looked for it over and over again, but nobody has seen it. The Parker Solar Probe is giving the first hints that this dust-free zone exists.

The objectives of the mission are obviously to explain the heating and the acceleration of the plasma in the coronal heating and acceleration of the solar wind. In other terms, what we are looking for are energy sources that we cannot see from Earth, and the Parker Solar Probe is giving us one possible smoking gun.

When the Parker Solar Probe got closer to the Sun, it saw kinks in the magnetic field. Magnetic fields essentially make an S-shape. They bend all the way back to the Sun and outward again in a matter of a few tens of seconds to several minutes. The reason why this is so important is that you cannot do that to a magnetic field easily. Creating this structure and maintaining it means that there is a big source of energy creating that. That's exactly what we are looking for.

Right: Our Sun from the first batch of solar images taken by ESA/NASA's Solar Orbiter on 30 May 2020



Surely with this mission, the fact that it's achieving so many milestones and performing so well, that's going to inform what kind of mission you could do next, and what sort of boundaries you could push.

You are touching on a very sensitive nerve there. Go back in history to the 1960s. There was a committee that proposed three key missions that NASA had to implement. One of the missions was a probe that orbits the poles of the Sun, which has already been implemented. This was the Ulysses mission. Now that mission is over. The second one is a probe that will orbit the Sun within the orbit of Mercury. That is the Parker Solar Probe. We did it after 60 years. It has been challenging, but we did it.

The third one is a probe that will fly out of the Solar System, very, very far away. We are working on that, but why have we started working on that? It's because we realised the success of the Parker Solar Probe.

Now the community is so bold. Realising that a challenging mission like the Parker Solar Probe can be so successful, we are able to do it for other missions as well. The outer solar probe is certainly one of them. It's an extremely challenging mission, but we started working on it at APL and hopefully one day it will see the light.

There is another idea out there, which is having a solar polar mission, which is an amazing mission. This is a mission that will fly above the poles of the Sun for an extended period of time, and that's also not easy at all. Getting a spacecraft out of the ecliptic is extremely hard, but again, realising the success of the Parker Solar Probe is pushing the community to be bold and start thinking about these big challenges.

The European Space Agency (ESA) recently launched the Solar Orbiter spacecraft in collaboration with NASA. Are there any plans to coordinate on observations with the Parker Solar Probe and the Solar Orbiter?

These two solar missions can complement each other in many ways. I can tell you that working together will provide the scientists – and also everybody else – with way more than the sum of the two missions.

I'm almost sure that with these two missions, and also if you add DKIST the Daniel K. Inouye Solar Telescope, which is a large solar telescope in Hawaii, this coming decade will be the golden age of solar and heliophysics research.

I don't think we have ever witnessed the amount of enthusiasm around the Parker Solar Probe, Solar Orbiter and DKIST as we are seeing now, and honestly we have never been able to achieve this much in such a short amount of time. Having a mission that is approaching the Sun like never before, having another mission that is flying above the ecliptic to see the poles for the first time and also having the largest solar telescope on the ground... it's amazing.

INTERVIEW BIO

2021

THE YEAR BRITAIN LAUNCHES TO THE MOON

Before humankind returns to the lunar surface, UK-built robotic spiders will be skulking across it. **All About Space** speaks to Pavlo Tanasyuk, the CEO of Spacebit, on spearheading an initiative to explore ancient lunar lava tubes

Interviewed by Lee Cavendish

For anyone looking to put the day in their calendar, when and where can we expect the launch of Spacebit's mission?
We don't know the exact date right now, but it's summer 2021. There can be a slight delay because of the supply chain. The main customer for the United Launch Alliance (ULA) Vulcan Centaur launch is Astrobotic. But we trust the ULA and Astrobotic to get us to the Moon safely and on time.

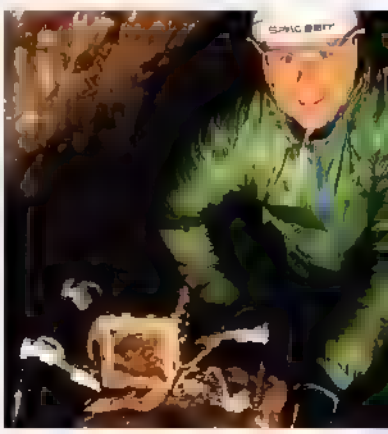
Have you mapped out where the Peregrine lunar lander is set to land on the Moon?
Lacus Mortis. It's north of the equator a little bit. It can get changed, but we expect that it will be there. The reason for that is because it's quite flat, but there is a potential lava tube in the proximity of our landing site. It's a bit of a stretch to say that we will enter a lava tube during our first mission, but that's our ultimate goal. That's why it has legs and not wheels, because it's designed in a unique way so that it can walk on rough terrain and crawl into some interesting spots.

Regarding the Asagumo rovers, these look absolutely fascinating, but in terms of engineering, what size are they, how do they move and how are they shielded from the unfiltered rays of space?
That's a good question. The size is, with the legs folded, we are talking about 16 to 18 centimetres long (six to seven inches) and about 14 centimetres (5.5 inches) tall.

No bigger than a toaster, for example?
Yes, it's basically like a nice toaster with legs, and a very expensive one. We have to protect the rover from the external environment, and that includes all sorts of radiation. It includes the Sun's radiation and its heat as well as some stronger particles.

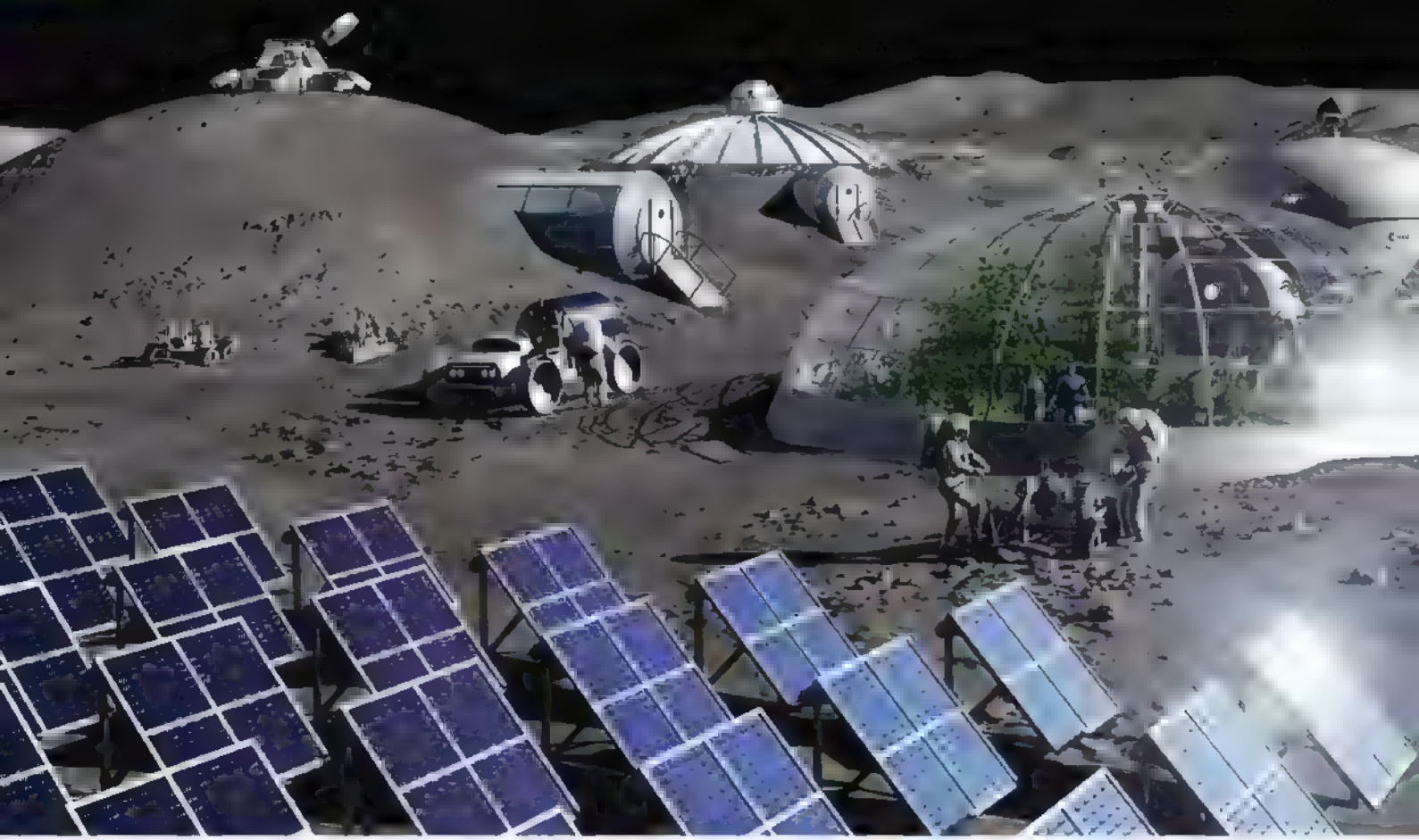
The major concern is the balance of the temperature. It is something which is important because our rover is quite small, and we have quite a few things inside. We have a battery, we have a transmitter, we have a motherboard and a controller for the legs - it's very complex machinery in something of that size. You can almost compare it to a CubeSat in terms of size, but the rover is slightly larger. However, because the CubeSat is usually in low-Earth orbit, it's not in deep space, and the environment is not as harsh in terms of the solar rays, and therefore it's not in a thermally unstable condition.

We will have to fly through deep parts of this space, in a very cold condition. Then when deployed it's going to be heating up to roughly 75 degrees Celsius (167 degrees Fahrenheit) when we land. Probably in a couple of days it will reach above 100 degrees Celsius (212 degrees Fahrenheit). The maximum that you can get on the lunar surface is about 130 degrees Celsius (266 degrees Fahrenheit). However, once a shadow looms over it becomes cold very fast. We're trying to build lunar rovers that can withstand these deviations.



Left: Spacebit's Asagumo rover weighs in at 1.3 kilograms (2.9 pounds)

Right: Tanasyuk believes that lunar lava tubes offer the perfect protection from harsh cosmic radiation



The rover has a very unique look with its spider-like legs. How does this give you an advantage traversing the lunar surface as opposed to using wheels?

Many people were sceptical about the legs - and some of them still are. Even though we have already demonstrated it can move on the surface of Earth, we still have to prove that it can do the same on the Moon, but yes, there is some scepticism from the scientific community.

Left: Tanasyuk announced Spacebit's lunar intentions at a New Scientist Live event in October 2019

But as a conceptual form it's a very interesting design because it can allow us to basically step over some obstacles. It can allow us to go in [lava tubes] at a certain angle. It can also allow us to maybe even jump on the Moon in certain conditions. It's basically like a spider. If you look at what nature has created, you don't really see anything built with wealth, and we are capable of going over hard terrain. It proves that sometimes you need legs to do certain specific tasks. If it's military combat and you need something to carry along a soldier, you can't really do that with wheels because of the terrain. The same applies to the Moon.

There are two things here to note. First of all, we're doing this because we really want to go into a lava tube, and we believe it's one of the better designs to do so. Secondly, I decided to go for this challenge because it's a cool design and I believe it's something different. It would be very obvious to go with the wheels as it's a much simpler way.

Sometimes we do regret choosing the legs because it's so much more challenging than two wheels. But it's a very interesting technology, and I believe that in our future on the Moon, and other celestial bodies, you will have robots with wheels and you will have robots with legs. That's why we have to be pioneers.

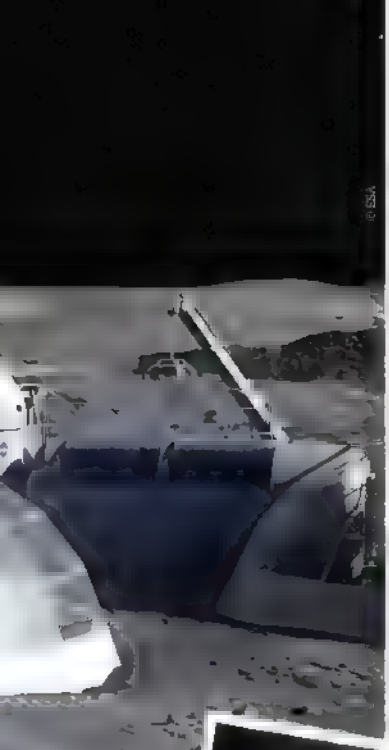
What scientific data can we expect on the return of the Asagumo rovers?

There are some limitations in terms of the size as you can imagine, so you can't really put all the technologies inside. The instruments that the Asagumo rover will be carrying will include temperature sensors, sensors that will measure radiation and other things. We also have a small tiny laser, which will be beaming light.

The reason for this is because we want to see if there are any small particles near to the lunar surface that are charged with electricity. The only way to do it is to shoot the laser really close to the ground. That will be helpful to see if there is an atmosphere on the Moon that is really close to the surface, which scientists believe might exist.

If the mission is successful, it will be massive in terms of Britain's contribution to space exploration and science. Do you think this mission will have a profound effect on the UK space industry?

I really hope so. We're trying to create some buzz around it because we'd like to drive STEM projects and drive some larger scientific projects as well. I was born abroad, but I've been living in the UK since 2006. I came here as a student and I didn't



Left: The future could see a human settlement on the Moon known as 'Moon Village'

Below: The Apollo missions have shown how beneficial it is to have both human and robotic explorers on the lunar surface

know that the UK doesn't have a single rover on the Moon – or anything on the Moon for that fact. When I learned that, it was a surprise. Why? Because it's one of the greatest nations in the world and has never been able to do something like that, which is really a shame. That's why I want to correct that.

Everybody knows that the US is doing a lot at the moment, and the obvious route for everyone including start-up companies, is to just move over to the US and take part in their missions because there is more money. But I believe that – especially with Brexit – we are in a good strategic position to progress with the future of space exploration. Lunar exploration comes first because it's closer.

In the past we used to send naval vessels around the world for trade and other purposes, and now we are more or less localised in terms of how we think. I believe that this mission could change the game, and we should be sending more spacecraft to different places on the Moon and other planets. I believe that the UK has the heritage and the spirit to do so.

You have a second mission planned for 2023. Is there anything you're able to share?

2023 is a larger mission. We will be sending a mothership, as we call it. It's going to be a larger rover, and it will host four Asagumo payloads inside. That way, even if we land far away from the lava tube, we can use our mothership rover to get there fast, and then we can use our small Asagumo rovers to go and explore. Also, you can sacrifice one of them to go and explore one of the more dangerous environments.

Lava tubes on the Moon are an unusual place to go and inspect. A lot of attention is currently focused on water ice at the lunar poles, which can be exploited as a resource. Why is exploring lava tubes so important?

Water is very important because obviously it's water. You can use it for technical aspects, such as fuel, as well as breathable oxygen. It's also easier to explain to the public. However, lava tubes are equally as important.

My belief is that in the future you will have to live on the Moon. There will be some settlements on the Moon – or as we call it 'Moon Village' – maybe by 2035 or around that time frame, so you will have to build some structures for people to live in, and it will take a tremendous amount of energy and resources to build something like that.

But if you have a lava tube, you already have an environment that is shielded from radiation and many other things. You are getting an environment where you can already store stuff, and you can live and work there. That's why one of the aspects of this mission is to help the future human exploration of the Moon. Robots and humans will be working alongside each other on the Moon, and I believe that exploring lava tubes is very important for future settlements.

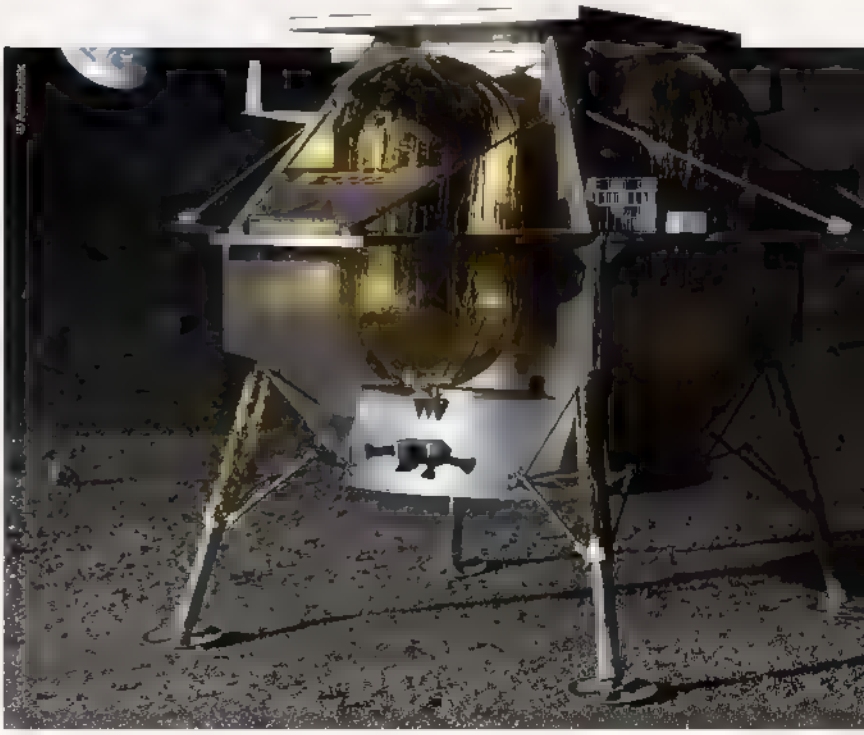
From a scientific perspective it's a very interesting environment because this is an environment that has been left alone for billions of years. For billions of years there has been no sunlight, and for billions of years there has been no lunar dust. The lava tubes have been shielded from all those externalities, which is not the case here on Earth. This means it's a very good potential site for science and to learn more about the universe.

This mission will help with pre-human exploration preparation. But also it's interesting to see if any resources are there that we don't know about. But in terms of the science itself, it's very valuable when trying to learn about how the Moon formed, for example.

Is there likely to be a chance for the public, schools and universities to get involved with the mission? If so, how?

We are planning on doing a lot of STEM activities and engaging with universities and schools in the UK. Our aim is to provide a certain level of granularity of data to the schools and universities for free.

This could help students run some experiments and to learn more. Or maybe we will even allow a certain data stream live from the lunar surface so they can do some live experiments as well. We believe that this kind of STEM engagement with the new generation is what is needed.



Right: In May 2019 Astrobotic was tasked by NASA to take as many as 14 payloads to Lacus Mortis

Deep Space

Go beyond the Milky Way and uncover the mysteries of the universe

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Planets could form from the ice-covered dust particles that circle these cosmic colossi

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"If there is a group of people who know how to be confined in a small space for months on end, it's astronauts."

DO EARTH-LIKE PLANETS ORBIT OUR GALAXY'S BLACK HOLE?

'Blanets' could form from the ice-covered dust particles that circle these cosmic colossi

Supermassive black holes (SMBHs) are theorised to be present at the centres of galaxies across the universe. They are Herculean celestial objects that consume gas and dust via an accretion disc and burp out jets of X-ray radiation from their core – jets so powerful they can be spotted from billions of light years away. This doesn't sound like a hospitable environment for planets, but recent research led by Dr Keiichi Wada, an astrophysicist at Kagoshima University in Japan, suggests it could be.

Wada and his research team believe that there could be tens of thousands of these black hole planets, or 'blanets', at the heart of the Milky Way. The formation of a planet is a complicated transition from small clumps of debris to enormous orbs of rock, gas and liquid. It's an even trickier process around a SMBH since not all of these circumnuclear discs can accommodate planet formation. These regions are far less dense than what is found around young stars, and the emissions near a black hole's event horizon can prevent gas and ice from accreting effectively.

Ice is an essential part of this formation process; it allows for debris to coalesce before the mass latches onto the sticky [illegible]. Some SMBHs only have ice orbiting them at a certain distance from their centre, where it is cool enough, known as the 'snow line'. Wada theorises that blanets can form beyond the snow line and form rocky planets – like Earth, except as much as ten-times larger – and gas giant planets similar to Neptune. These rocky blanets would take around 10 million years to come to fruition, and if conditions are right they can accrete even more debris, enabling them to evolve into gas giants.

The formation of blanets can only happen around a percentage of SMBHs, however. If a black hole is extremely powerful and active, it will have an increased radiation output that will melt ice and make it impossible for a significant amount of accretion. Think of it as throwing two pebbles together and trying to make them stick, as opposed to throwing two snowballs together.

Sagittarius A* (Sgr A*), the black hole at the core of the Milky Way, is cool enough to allow for ice in its circumnuclear disc. According to Wada's calculations, thousands of blanets are likely to have been born around it – the problem, however, is that it's extremely unlikely that we [illegible] observe one, since they would be [illegible] light, buried [illegible]

"WADA THEORISES THAT BLANETS CAN FORM BEYOND THE SNOW LINE AND FORM ROCKY PLANETS"

Above: Could supermassive black holes have planets in orbit around them like stars do?

SOLVING THE DARK ENERGY ENIGMA

Three exciting projects will soon survey the sky in order to answer an intriguing question: what is dark energy?

The universe is a funny thing. Astronomers work their whole careers to understand what it's made of, yet they are also open to the idea that they could be as far away from the truth as possible. The key to understanding the large-scale structure of the universe is figuring out what dark energy is. This mysterious form of energy is related to the expansion of the universe. After conducting experiments related to this expansion, astronomers have at least been able to determine that dark energy makes up 68 per cent of the universe. The rest is dark matter – the equally mysterious matter that cannot be directly observed but interacts gravitationally with regular matter – and baryonic matter. This we can observe; it is what makes up galaxies and everything within them.

"Dark energy has two noticeable effects in the universe. The first effect is on the expansion history of the universe. Dark energy has caused the expansion of the universe to accelerate in the last few billion years. Observing supernovae that have occurred in the last 10 billion years gives us a very good measure of the expansion of the universe," Dr Jason Rhodes, project scientist of NASA's Wide Field Infrared Survey Telescope (WFIRST) space observatory, tells All About Space. "The second effect dark energy has is on the distribution of matter in the universe. This distribution, and how that distribution changes over time, is given by an interplay between the attractive force of gravity pulling things together and the repulsive nature of dark energy pushing things apart."

"Living in a universe predominantly made up of dark energy and not knowing much about it seems strange. However, there are some exciting projects on the way that are looking to scrutinise this currently theoretical substance. Three notable candidates will take our most recent findings, apply it to state-of-the-art engineering and analytical techniques and delve headfirst into the dark universe in an attempt to understand what dark energy is.

Left: The universe is made up of countless objects spanning across billions of light years

This trio consists of NASA's WFIRST space observatory, the European Space Agency's (ESA) Euclid space observatory and the Dark Energy Spectroscopic Instrument (DESI) attached to the Mayall Telescope at Kitt Peak National Observatory in Arizona. Together these three dark energy surveyors will use a variety of techniques to understand the distances between galaxies and the acceleration of their expansion and construct an accurate three-dimensional model of what our universe looks like.

"So far all observations indicate a relatively straightforward cosmology: the universe contains cold dark matter which evolves according to the theory of general relativity with a cosmological constant lambda – the famous lambda-CDM concordance model," Euclid's project scientist Dr René Laureijs explains to All About Space. "Unfortunately, this model of the universe cannot be unified with the Standard Model of elementary particles that is quantum theory. There is a fundamental problem. I hope that these missions can shed some light on this."

Our currently accepted theory is that the universe consists of 'cold dark matter' and a cosmological constant. Cold dark matter, or CDM, is dark matter that moves slowly compared to

What is the universe made of?

There is much more to the cosmos than what meets the eye

68%

Dark energy

Dark energy makes up most of the universe. It is believed that this is the driving force behind the expansion of the universe, which Edwin Hubble observed in 1929.

27%

Dark matter

Dark matter refuses to be seen, but astronomers have observed its gravitational effects on galaxies and other astronomical observations.

5%

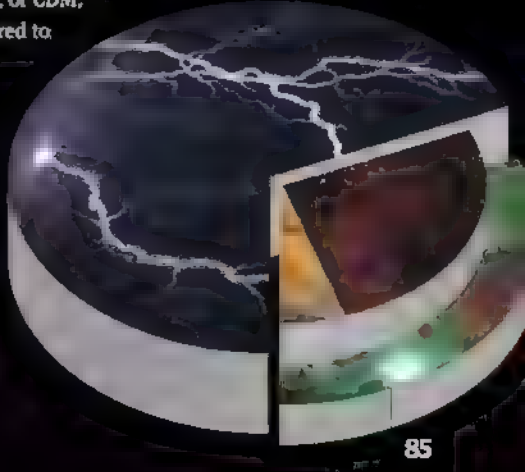
Baryonic matter

This is regular matter that can be seen and is composed of particles called baryons, but it only makes up a minute five per cent of the universe.

32%

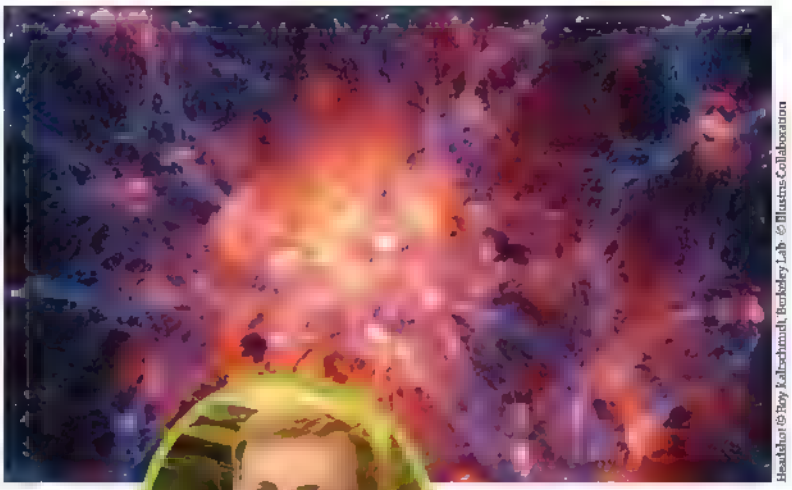
All matter

Even when you combine all matter, it still only makes up a third of the entire universe. This shows the overwhelming bias towards dark energy.



the speed of light, and a cosmological constant, or lambda, is the simplest form of dark energy proposed by Albert Einstein in 1917. It was included in Einstein's equations as an 'anti-gravity' constant to explain why the universe expands as opposed to collapsing under its own gravity. However, as Laureys explains, this theory has trouble explaining the behaviour of the cosmos' smallest particles. Before cosmologists can begin to intertwine the two theories, they need to construct a large-scale map of the universe.

The DESI instrument is operated by the Lawrence Berkeley National Laboratory in California, and it achieved first light on 22 October 2019. DESI's host is a modest telescope, but has been active in the scientific community since 1973, and was the second-largest telescope in the world at the time. The Mayall Telescope has now been fitted with an innovative instrument that consists of 5,000 fibre-optic 'eyes'. Each cable is capable of capturing the light of a single galaxy and splitting it into a spectrum of light for astronomers to carefully analyse. Within a 20-minute observing time, this instrument is capable of gaining spectroscopic data on 5,000 galaxies simultaneously. "The size of this survey will be huge. In the first five years of operation we will have measured the distance to more galaxies than previously measured by all other telescopes in the world combined," says DESI's project scientist David Schlegel of Lawrence Berkeley National Laboratory.



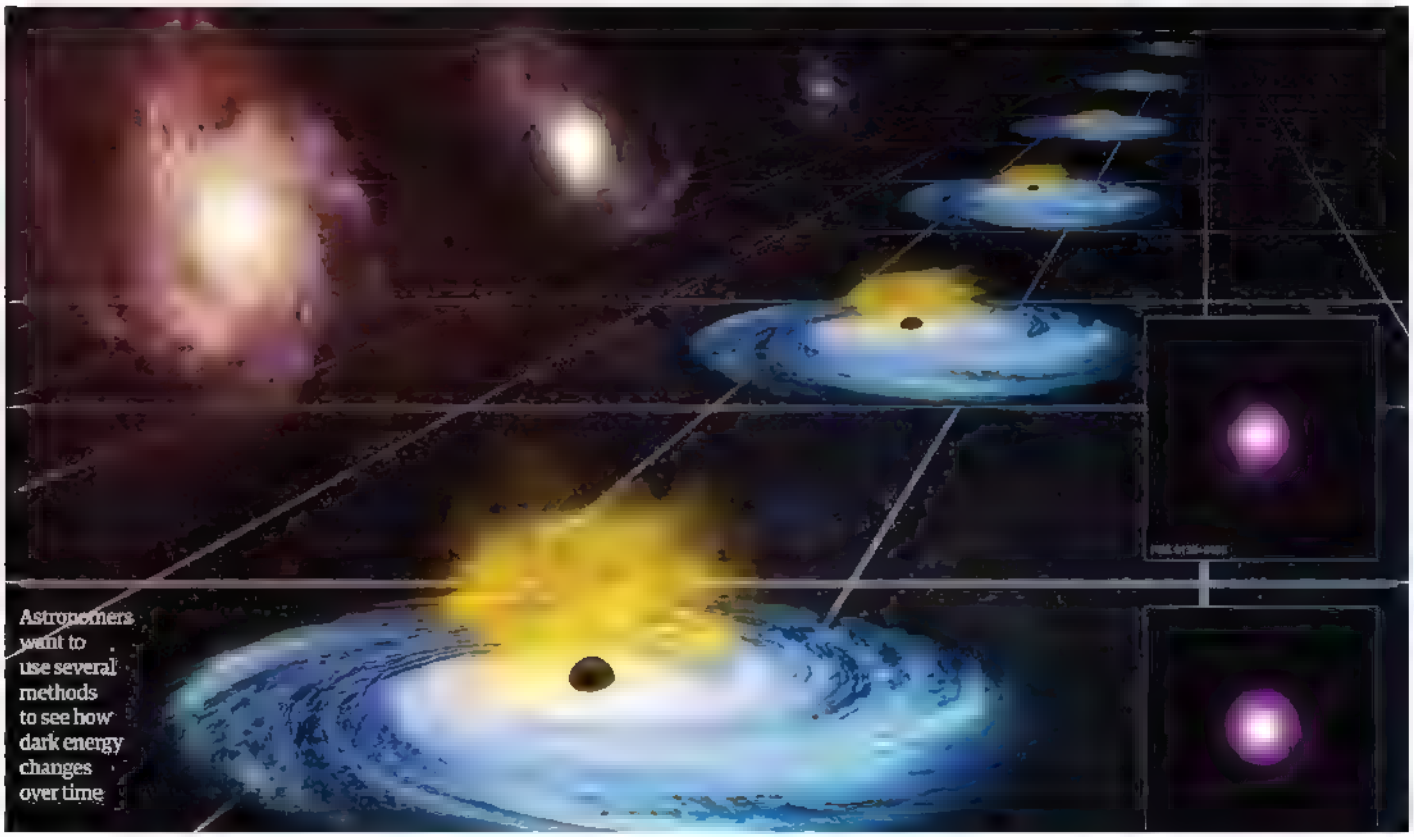
Heathcot © Roy Kaltschmidt, Berkeley Lab - © Illustris Collaboration

Right: The structure of galaxies and clusters appear as a 'cosmic web', which could be the key to understanding dark energy

Right: Schlegel is project scientist of DESI, which will analyse the spectra of millions of galaxies

Galaxies are key to grasping the universe and its past. Since the time of Edwin Hubble, astronomers have been studying distant galaxies and their spectra. By breaking up the light spectrum of a galaxy, astronomers are able to determine the shift of absorption or emission lines to reveal the galaxy's distance from Earth. It was with this technique, referred to as redshift, that Hubble and his space telescope namesake were able to determine that galaxies at farther distances are receding at a faster rate than nearer galaxies.

Now DESI is on a mission to collect data on as many as 35 million galaxies and 2.4 million quasars - extremely luminous and active galaxies - in one-third of the total sky area over a five-year period. This will allow astronomers to look back in time to roughly 11 billion years ago, approximately 2.8 billion years after the Big Bang. "DESI helps us understand the accelerating universe through the structure of this 3D map because the features on this - positions and clusters of galaxies - could vary significantly as we look deeper into the universe," explains Schlege



Astronomers want to use several methods to see how dark energy changes over time

© NASA

A trio of cosmic pioneers

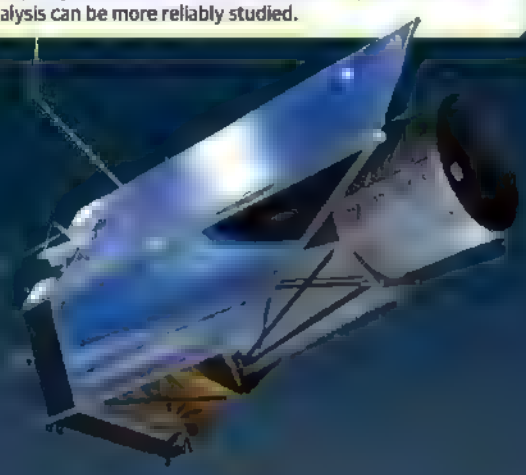
These three projects will each examine the universe in their own unique way

Euclid

Operator: ESA **Location:** Sun-Earth Lagrange point L_2

First light: 2022

Euclid is destined to study both dark matter and the dark universe by observing both weak gravitational lensing effects and baryonic acoustic oscillation 'standard rulers'. Euclid's ability to gather data via two reliable techniques means the analysis can be more reliably studied.



Wide Field Infrared Survey Telescope (WFIRST)

Operator: NASA **Location:** Sun-Earth Lagrange point L_2

First light: 2025

WFIRST is NASA's next flagship telescope and will devise a detailed map of the distribution of galaxies throughout the ages. This map will be compiled from data collected from supernovae, weak gravitational lensing and a variety of galaxy clusters.

Dark Energy Spectroscopic Instrument (DESI)

Operator: Lawrence Berkeley National Laboratory, University of California, Berkeley

Location: Kitt Peak National Observatory, Arizona

First light: 2019

The sheer volume of data that will be collected by the DESI instrument and its 5,000 'eyes' will keep astronomers busy for years. This cutting-edge technology can potentially provide data on 5,000 galaxies in a 20-minute time window. The spectroscopic data collected will allow distancing measurements and will map the distribution of galaxies back billions of years.


© ESA

Left: As the project scientist of Euclid, Laureijs is helping to unlock the secrets of dark energy

"For instance the map close to us is stretched out a lot more than it should be because of this acceleration due to dark energy. And then in the early universe, when there's not as much dark energy, it shouldn't be as stretched out, but this is where we don't have much data yet. Depending on when dark energy was pushing the universe apart, it will push apart different parts of the map. This data will help us eliminate a number of theories about the way dark energy works."

Next to receive first light will be the ESA's Euclid mission, which will focus its efforts on the grander dark universe - both dark matter and dark energy. This space telescope is planned for launch in 2022. Its equipment includes a 1.2-metre (four-foot) primary mirror, fitted in a Korsch telescope, which will explore the cosmos in visible and near-infrared light. The mission duration is set at six years, and in this time it "will measure the expansion of the universe starting at a redshift of $z=2$, which corresponds to a look-back time of some 10 billion years ago, until now. The measurement will cover the period that the universe turned from a decelerating expansion caused by the gravity of the dark and ordinary matter into an accelerating expansion due to the growing prominence of the dark energy," explains Laureijs.

Euclid will measure the universal expansion and the distribution of dark matter using two different methods: weak gravitational lensing and baryonic acoustic oscillations. Weak gravitational lensing is better suited to understanding dark matter because by observing the visual dysmorphia of a background galaxy – an example being the famous Einstein Ring - astronomers can determine the amount of dark matter in the foreground galaxy

What is the fate of the universe?

Astronomers are unsure about the future of dark energy, and it could play a huge role in the fate of the universe

The Big Rip

If the rate of expansion due to dark energy continues to accelerate, it is possible that space-time will be slowly torn apart.

Discovering a cosmological constant

Einstein proposed a 'cosmological constant' along with his theory of gravity that could be causing a steady rate of cosmic expansion.

cluster as it uses its influential gravity to bend light. However baryonic acoustic oscillations are better suited for probing dark energy by seeing how the same fluctuation oddities seen in the cosmic microwave background (CMB) have influenced the spatial distribution of galaxies and clusters. This technique will provide measurements of enormous cosmic structures that are influenced by the opposing forces of gravity and dark energy.

The baryonic acoustic oscillations' spatial distribution originates from when the universe was a ball of hot and dense plasma, even before when neutral hydrogen began to form, which is also known as the epoch of recombination and is the predicted source of the CMB. The baryonic acoustic oscillation technique is referred to as a 'standard ruler' due to the reliably constant distance between galaxies, and can be a powerful tool when measuring the growth of cosmic structures within the overall expansion of the universe.

"The presence of a force related to a substance named dark energy is theory but Euclid will provide sufficient observational accuracy to prove the validity of the theory. In addition we will have sufficient accuracy to determine whether the acceleration is constant", says Laureijs.

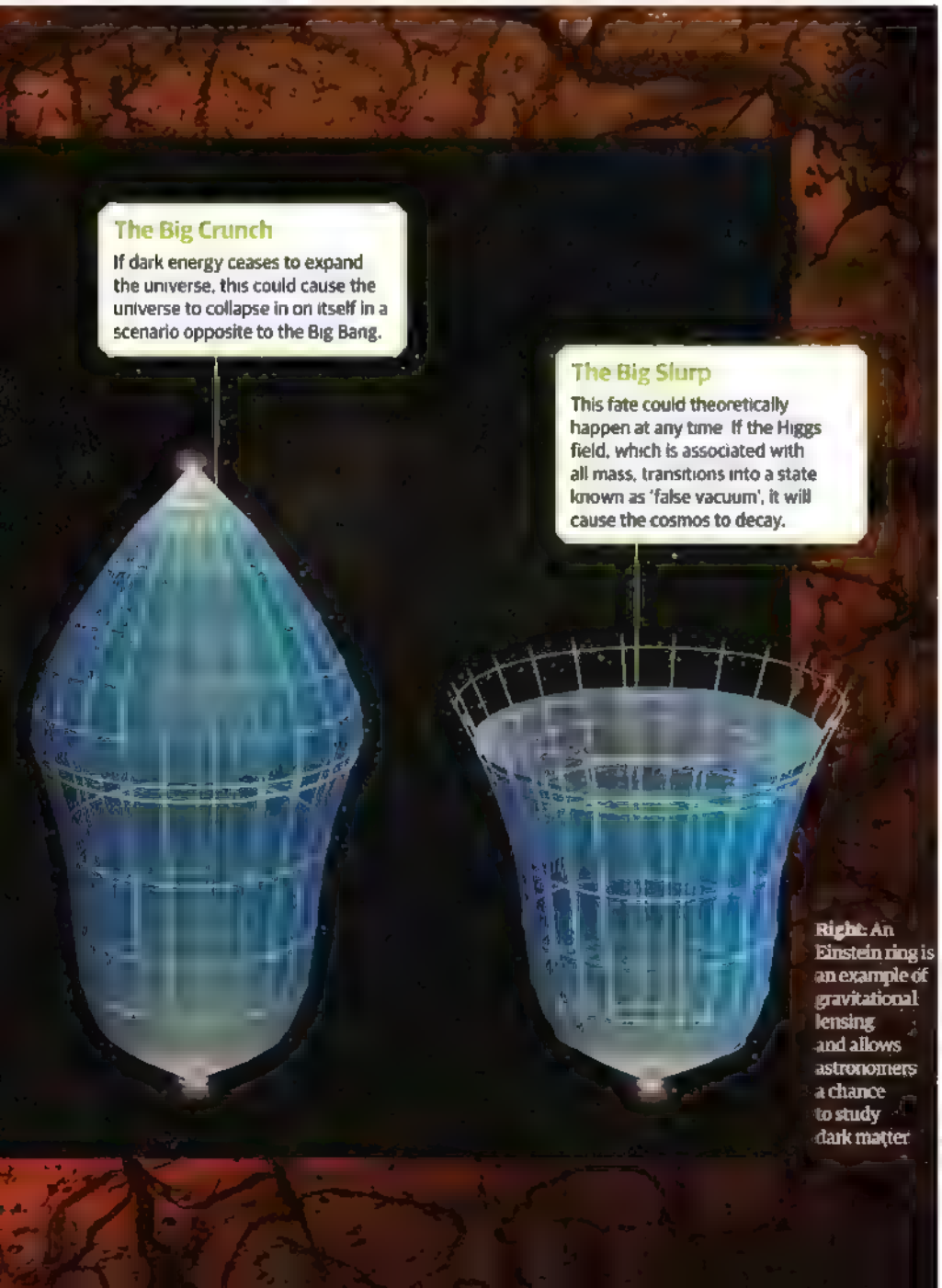
Lastly, the telescope that completes this triad - if Trump's administration doesn't scrap it first - will be WFIRST due to launch in 2025. This is one of the successors of the Hubble Space Telescope, its build looks similar, but it is much more powerful. "The near-infrared camera on the venerable Hubble has one megapixel," explains Rhodes. "Each of WFIRST's 18 near infrared detectors has 16 megapixels, giving WFIRST an astounding 288 megapixels. Given that the WFIRST telescope is the same size as Hubble, WFIRST will have the same resolution and light-collecting power, but with a camera that can view nearly 300 times as much sky in a single image."

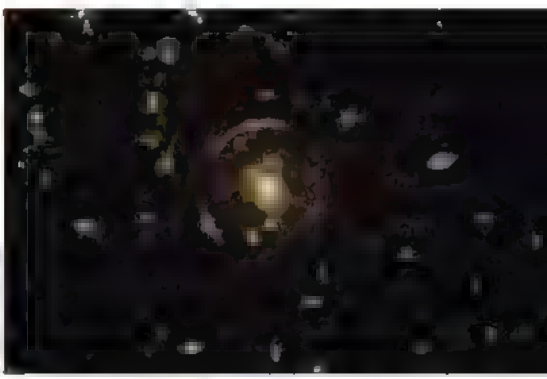
The WFIRST team plans to utilise three different scientific methods in an attempt to finally prove the existence of dark energy. "Using supernovae as standard candles to measure the expansion history of the universe, using weak gravitational lensing and using the clustering of galaxies," Rhodes divulges. "WFIRST will use all three of these techniques to make multiple measurements of both the time evolution of the distribution of matter and the expansion history of the universe. Using multiple techniques allows us to have independent cross-checks of our results. Measuring both the matter distribution and expansion history allows us to distinguish between many different dark energy theories."

However, this dark energy inspector may not be able to cast its gaze upon the cosmos for a while yet. Although the designated launch date is 2025, this project is dependent on the construction completion and launch of the James Webb Space Telescope (JWST), which has had delays in droves. With WFIRST estimated to cost a maximum of almost £3.4 billion ($4 billion), it may take a while to reap the benefits.

When the time comes that these projects are up and running - and most likely in the case of DESI have already finished their observing - we could be living in a world where dark energy is less elusive and less mysterious. This may sound optimistic but with this many dedicated and technologically advanced instruments scanning the sky in remarkable detail, astronomers may have a better understanding of what dark energy is, how the universe was born and also how it will end.

"Based on our current understanding of dark energy, we think the universe will end in a Big Rip in the very distant future. However, we are still in the early days of studying dark energy and we don't even know if the dark energy evolves over time," says Rhodes. "Our guesses now are just that guesses, until we have a lot more data that helps us distinguish between the many theories of dark energy that fit the limited data we have now."





Right: An Einstein ring is an example of gravitational lensing and allows astronomers a chance to study dark matter

THE IMPOSSIBLE GALAXY

Hoag's Object is strange enough as it is, but astronomers can also see a galaxy within the galaxy within a galaxy

Reported by David Crookes

The universe is a gorgeous place, but some images have a greater power to stop you in your tracks than others. "Hoag's Object is fascinating because of its aesthetic value; it's just a beautiful thing," Dr Noah Brosch tells All About Space about one particular intergalactic gem. Indeed, one glimpse at its perfect circular ring of blue stars around a golden central ball and there's no denying that most people would find it hard to tear their eyes away.

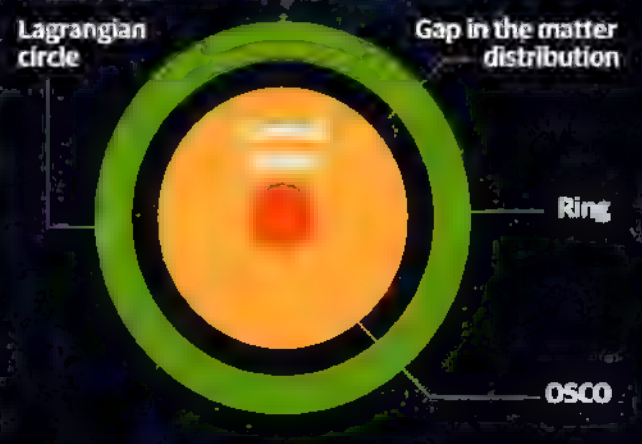
The ring-shaped galaxy was discovered by American astronomer Arthur Hoag in 1950. He had been working at the US Naval Observatory and originally thought the object was an ejection of ionised gas from a red giant star in its last throes of life – a planetary nebula.

Rejecting his own hunch on the grounds that the ring's light was not being emitted at the expected wavelengths, he later theorised that the whole thing may have simply been an Einstein ring – an optical illusion caused by gravitational lensing of the source's light. After all, in the very early images of the galaxy, a blue ring was seen to encircle a yellow core, and the Einstein ring was a suitable explanation. As clearer images of Hoag's Object came into view in the late 1980s, however, that idea was soon dismissed too.

What remains is a mystery that astronomers are keen to figure out. The pictorial evidence is of a galaxy within a galaxy – two stellar circles separated by a dark gap – but studies have shown that they are both at the same distance from Earth since they have an identical redshift. This points to them being one galaxy rather than two. In actual fact, it's a peculiar galaxy quite unlike the majority of others. It is an immense eye-catching structure of gigantic proportion.

In terms of specifics, the red, dead inner core is 17,000 light years across. The dark ring around it measures 50,000 light years and the overall object from one side to the other is 120,000 light years, making it slightly larger than the Milky Way. The outer bright ring of stars is 70,000 light years away from the central component. What is perhaps most stunning, though, is that if you look even closer you can see another ring-shaped galaxy in the gap, pointing to a galaxy within the galaxy within a galaxy. It is simply jaw-dropping.

This has certainly been the takeaway of an image that has been doing the rounds of late. Taken by the Hubble Space Telescope and processed by geophysicist Benoit Blanco, the billions of blue stars are clearly separated from



HOAG'S OBJECT BY THE NUMBERS

1950
The year it was discovered by Arthur Hoag

8 billion
Number of stars contained in the galaxy

600 MILLION
Number of light years away from Earth

120,000
Overall light-year distance of the entire galaxy

70,000
Light years between the ring and the central part

1
Another ring galaxy visible within the gap

16.2
Apparent magnitude

3 billion
Years in the past that a collision between two galaxies may have happened

0.1
Percentage of all known galaxies being ring galaxies

24,000
Light-year distance of the inner core

Above: According to Noah Brosch, extreme bar instability in a galactic disc such as this one could have formed Hoag's Object

the dense inner sphere made up of reddish stars. The other ring galaxy is visible as a red circle within the empty space - it's actually far away and not part of Hoag's Object itself. But the fact that it lines up in such a way that telescopes can pick up on it is nevertheless startling and a real cosmic coincidence.

"I think it's incredible that there's a ring galaxy in the background of a ring galaxy and that's why I choose this object for an advanced processing project," Blanco tells us, having made use of an artificially intelligent denoising algorithm. "I think it illustrates how infinite our universe is – the fact that in this case, you can look at a very unusual object and find one at the back." But how are these peculiar galaxies forming?

First things first. Hoag's Object - which is 600 million light years away from Earth towards the constellation of Serpens - is not a one-off, or even a two-off, given that we can see another peeking from the back. "Tens or more ring galaxies are known, but because of inclination and distance, none are as impressive as Hoag's," explains Brosch, who works at the department of astronomy and astrophysics and the Wise Observatory at Tel Aviv University in Israel.

Even so, that only accounts for about 0.1 per cent of all known galaxies, and it doesn't make such peculiar galaxies, which also include NGC 1291 and PGC 1000714, easier to fathom. There have even been suggestions that an intelligent species is behind the phenomena, but those are perhaps the easiest to discard. "I think that explanation is all wrong," Blanco says. "When a very unusual event is observed in the universe, we think about aliens, but it's just that the universe is infinite and everything that can happen does seem to happen."

So what could account for the processes involved in Hoag's Object's formation? "The most probable explanation is that a spiral galaxy has been captured by a spherical galaxy, but it's unique for such a collision to create a perfect ring," Blanco says of an event which would have affected its gravitational pull. Such a thing is believed to have happened to other ring galaxies, resulting in new elliptical shapes, mergers or density waves. "It's likely to have happened because of a random collision 3 billion years ago that was so perfectly done, a part of the spiral material fell into the spherical and the remaining spiral created a perfect ring," he continues. Yet no one can say for certain.

Indeed, in 1985 Brosch suggested that Hoag's Object was a result of instability in a barred spiral galaxy billions of years ago. He theorised that the bar would have rotated, forcing gas to be pushed to

the outskirts where a ring would not only form, but stars and planets would end up being created.

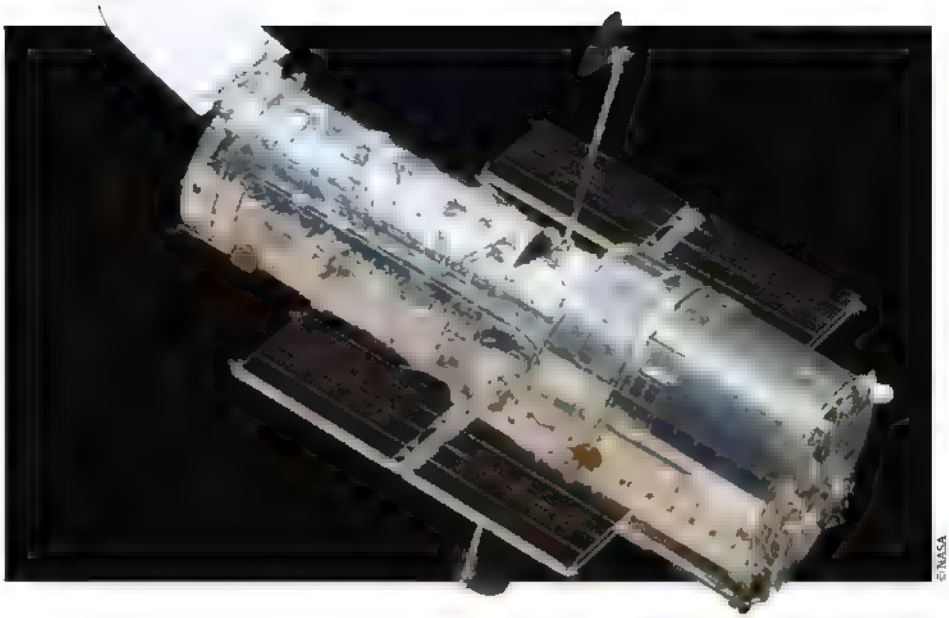
Brosch also hypothesised that any old and dead stars would sink into the nucleus as the bar became used up and frittered away. But other scientists argued that it didn't account for why that central part of the galaxy is spheroidal rather than misshapen or elongated. With no evidence that the galaxy was barred to begin with, competing theories were worked upon.

In 1987 François Schweizer, W Kent Ford Junior Robert Jedrzejewski and Riccardo Giovanelli suggested Hoag's Object had formed from a merger with a smaller lightweight galaxy. The gravity of the heavier elliptical galaxy tore the visitor in such a way that the gas settled into orbit. With the heavier galaxy forming the core, the gas lends sufficient fuel for the formation of stars that eventually produced a separate ring. In this sense it would be on the same lines as a polar-ring galaxy which are thought to occur when a couple of galaxies gravitationally interact with one another, producing an outer rotating ring of gas and stars.

One problem is that there is so much gas and stellar mass in that ring that it would have to have come from a galaxy far greater than a dwarf, in which case the disruption to the original galaxy would have been so great that Hoag's Object could not have formed in the way it has. There is also an issue of there being no sign of a second galaxy that could have collided, even with the use of the most sensitive of telescopes. To that end, Brosch revisited Hoag's Object in 2011 with Ido Finkelman, Alexei Moiseev and Ivan Katkov. Their paper said the elliptical core formed in the early universe, with the surrounding disc being created afterwards by "prolonged 'cold' accretion of primordial gas from the intergalactic medium".

In many ways their study was a continuation of Schweizer's theory. Kinematic data suggested Hoag's Object is a normal disc galaxy with a low-density hydrogen iodide disc that accretes onto the spheroid, and because of its lack of density forms stars in the ring. It's a theory that supposes gas floating in space is pulled in via gravity.

"My personal opinion is that the central elliptical like object is old," Brosch affirms. "The star-forming



© NASA

Above: The Hubble Space Telescope has been giving us a very close look at Hoag's Object

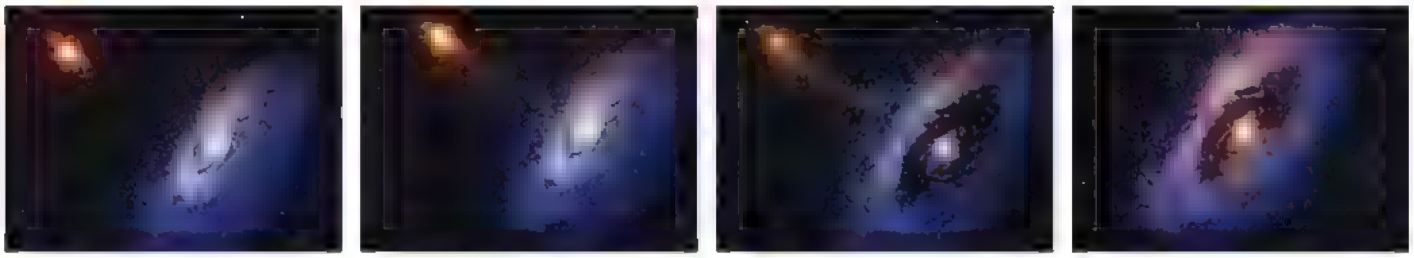
© BAAS

Right: American astronomer Arthur Hoag discovered the unusual ring galaxy in 1950 that became known as Hoag's Object

"I think it's incredible that there's a ring galaxy in the background of a ring galaxy; that's why I chose this object"

HOW HOAG'S OBJECT COULD HAVE FORMED

The possible steps taken towards creating an odd ring-shaped galaxy



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1 A lightweight galaxy approaches a larger one

According to a study headed by François Schweizer in 1987, a lightweight galaxy may have come into close enough proximity to a heavier, elliptical galaxy for a major accretion event to have taken place.

2

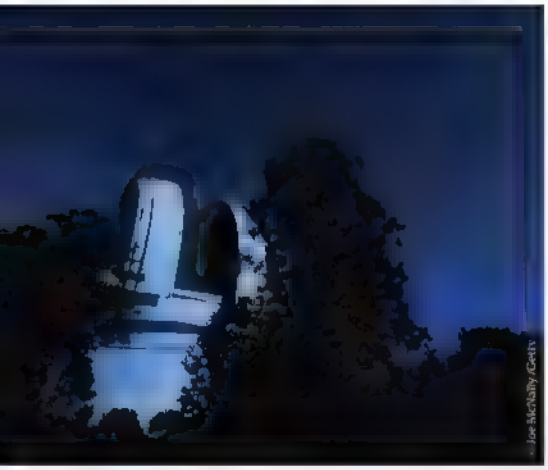
At some stage – likely some 2 to 3 billion years ago – there would have been some level of interaction between the two galaxies which, short of a merger or collision, caused the mass to transfer to Hoag's Object.

3

As the gravity of the heavier galaxy ripped the lighter one apart, transferred gas from the lightweight galaxy settled into orbit and fuelled the mass formation of stars, which over time formed a distinctive ring.

4

Any leftover detritus was then blown away into the universe over many years, which accounts for why there is no firm observational evidence of the event. Such scientific theory continues to be debated, however



THE THEORIES

What could account for the Saturn-like ring around this peculiar galaxy?

Collision between two nearby galaxies

Most ring-shaped galaxies are caused by a small galaxy colliding with a larger disc-shaped one, and while there is no evidence of a smaller galaxy having existed in the proximity of Hoag's Object, a collision remains a possibility. It would have torn a hole through a regular disc-type spiral galaxy and altered its gravitational pull.

A close encounter of two galaxies

Rather than colliding, there could simply have been a close encounter of two galaxies which resulted in the pulling in of gas from one to the other via gravity. Some suggest that the surrounding ring could also have been caused by prolonged accretion of primordial gas which eventually led to the formation of material.

Instability in a barred spiral galaxy

Brosch's hypothesis in 1985 suggested the ring formed in a similar manner to rings in barred spiral galaxies – that is, without any interaction and through slow internal evolution. With angular momentum transferred by the bar to the outer disc, gas is driven from the centre, creating the star-forming ring.

An alien-made structure

Joseph Voros of Swinburne University of Technology studied the possible "evolution of long-lived intelligent engineering species" which may have removed or lifted star systems and stellar material from galaxies, leaving a ring. He poses: "Is Hoag's Object an example of galaxy-scale macro-engineering?"

Top: This is the unbarred lenticular galaxy that can be seen shining from behind Hoag's Object

Above (right): An image created of Hoag's Object by Mike Herbaut using the free software program ESA/ESO/NASA FITS Liberator

Above (left): Hoag's Object was clearly visible on the Palomar Star Survey, but was missed off of a galaxy catalogues

ring is relatively young, and was formed by recent accretion of gas-rich material.

"This happened either by the tidal disruption of a dwarf galaxy followed by the ring formation, or by the direct accretion of gas and dust from intergalactic space with the inflowing material coming along a dark-matter filament that did not reach to the centre where the elliptical core is."

But what is stopping the outer ring from being pulled into the core? Why is this massive ring with ongoing star formation leaving a great gap between the two parts? To help answer this, in 2018 Elena Yu Bannikova from the Institute of Radio Astronomy of the National Academy of Sciences of Ukraine wrote a paper called "The structure and stability of orbits in Hoag-like ring systems".

In it she sought to explain where the forces between the core and the ring are gravitationally balanced. Through a series of mathematical equations she found that this was on the inner section of the ring – an unstable equilibrium called the Lagrangian circle. Furthermore, she found the outermost stable circular orbit (OSCO) is around the central galaxy.

"The masses of the central galaxy and the ring around it are comparable with each other," she tells **All About Space**. "The gravitational forces from the central galaxy and from the ring are acting in different directions, so there is a region where the gravitational field of the central galaxy is much stronger than from the ring, and the stars can move here in a circular orbit. There is also a region where the gravitational force from the ring is much more, so the stars will move around the ring.

"But there is also an intersecting region where particles and stars cannot move in a circular orbit due to competition between the gravitational forces from the central galaxy and the ring. We can say that the particles in this region do not belong in terms of gravitational attraction to either the central galaxy or the ring. It was surprising for me."

This accounts for why there is a gap in the matter distribution "where the circular motion is not possible due to the competition between the gravitational forces by the central mass and the ring" – that is, a great area where no stars or gas particles can orbit. It doesn't explain how it got to that state in the first place, but it points to why the ring remains and perhaps how the ring grew.

So what of that other ring-like galaxy that can be spotted far away behind Hoag's Object – the one catchily called SDSS J151713.93+213516.8 that has had a fair bit of recent media coverage since NASA made it its astronomy picture of the day on 27 November 2019? Unfortunately, although it can be clearly seen between the nucleus and the outer ring, it is too distant to get a proper close-up look, but the fact that it is there, in the same image as one so stark as Hoag, is simply delightful given their rarity. Both are likely to continue to fascinate astronomers for many years to come.

HOW ODD

There are many other weirdly formed galaxies out there

It looks like a penguin

NGC 2936 is 326 million light years away and it resembles a penguin, porpoise or dolphin depending on whose opinion you seek. It's actually a two-galaxy system, with an egg-shaped galaxy beneath, called NGC 2937.

These galaxies are interacting

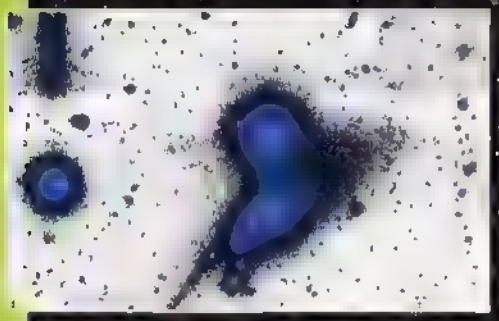
The peculiar spiral NGC 3808A and the irregular NGC 3808B are known collectively as Arp 87 and they're perhaps in a pre-merge state, having been very close to smashing into each other a few billion years ago.

Tip your hat to this one

NGC 4594 is known as the Sombrero because it resembles a wide-brimmed hat with a bulge in the centre and a dark dust lane around it. Just 28 million light years from Earth, that bulge comprises several star clusters.

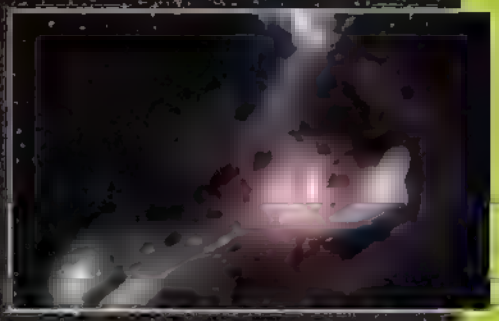
A supernova supersite

Messier 83 is a barred spiral galaxy in the constellation Hydra that's so bright it can be viewed using binoculars. Known as the Southern Pinwheel Galaxy, its swirls of pink and purple are punctuated by six observed supernovae.



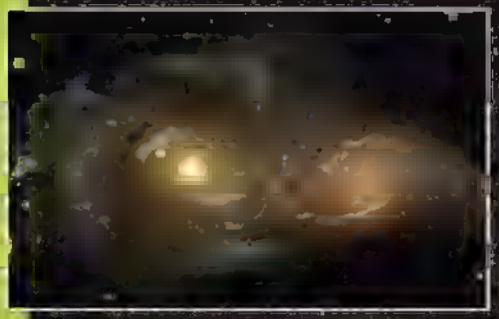
A giant tadpole of a galaxy

This disrupted galaxy was identified by astronomers from Israel, the US and Russia. Created by a cosmic collision, the image shows an elliptical head and a long, straight tail that is 500,000 light years long.



The universe's most luminous galaxy

An extremely luminous infrared galaxy, W2246-0526 is 350 trillion times as bright as the Sun. In 2018 scientists observed it stripping close to half the mass of at least three of its smaller neighbours.

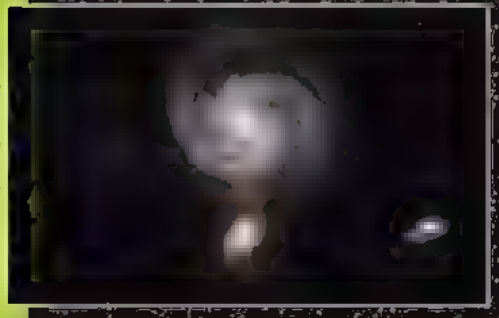


A pair of eyes in the sky

Looking like an evil pair of eyes, NGC 2207 and IC 2163 are colliding spiral galaxies in the constellation Canis Major. The eyelids were formed by dust and stars following the interaction between the two galaxies.

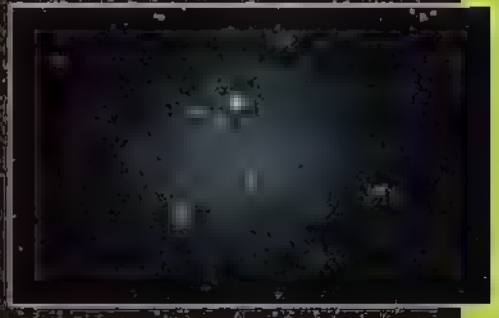
A highly energetic galaxy

The elliptical galaxy NGC 474 in the constellation of Pisces shows multiple layers of emission that could be tidal or related to debris that has been left over from the absorption of many small galaxies.



Have a heart – or two

Spiral galaxy NGC 7674 has been seen to have a couple of radio jets with an S-shape. This could indicate the presence of a binary black hole. In this case, they would be a light year apart. The galaxy is likely a merger.



Galaxies devoid of dark matter

That's what astronomers saw in a wide-field imaging survey of the ultra-diffuse galaxy NGC 1052-DF2. Despite being as large as the Milky Way it has 200-times fewer stars, making it appear translucent.

WHITE DWARFS ARE THEY THE KEY TO LIFE?

New research suggests that we've been looking for other civilisations in all the wrong places

Reported by Colin Stuart

Picture a planet that hosts life elsewhere in the universe. The kind where aliens wander around on its surface, going about their daily business much like you or I. What kind of planet comes to mind? Normally the answer is one very much like the Earth because our planet sits in a temperature sweet spot. We're not too close to the Sun that we boil, nor too far that we freeze. Astronomers call it the Goldilocks zone because, like the porridge in the classic fairy tale, conditions are just right. Ideal for the all-important liquid water that is crucial to the existence of every life form on the planet.

For that reason, much of our work to look for life beyond our Solar System has centred on the search for Goldilocks planets around stars like our Sun. Yet if recent research is anything to go by, we could be making a fairly sizeable mistake. "We could be missing a prime spot because of our own biases," says Paul Sutter of Stony Brook University in New York. Perhaps the best place to look for life is around dead stars.

It's no secret that our Sun will eventually die. The hydrogen supply powering its energy creation will run out. After switching to burning helium instead, our star will bloat into a red giant, engulfing Mercury and Venus in the process. The Goldilocks zone will be pushed beyond our planet. "Earth will no longer be viable," says John Gertz, who sits on the boards of both SETI, the organisation behind the search for extraterrestrial intelligence, and Breakthrough Listen, a $100 million (£77 million) initiative to scour the skies for signals from alien life. Any civilisation facing such a prospect will have to act or perish. Gertz attempts to 'get into E.T.'s mind' in a recent scientific paper published in the *Journal of the British Interplanetary Society*. His is an outsider's perspective. Although he studied medicine at university, he's not an astronomer or astrophysicist. Instead he's an entrepreneur who runs a successful film production company in the movie heartlands of California. As a business person, he c... the problem from an economic angle.

...giant planet like Jupiter, both of which would get considerably warmer under the increased glare of the dying star. But even that is not an easy path. "We're talking about a Solar System in great distress," Gertz says. The solar wind – the breeze of charged particles howling away from the Sun and other stars – becomes a hurricane. Solar flares get more frequent and intense. According to a recent study led by Dimitri Vera... at the University of Warwick, this will have a knock-on effect on the asteroid belt too. "The...

© ESA

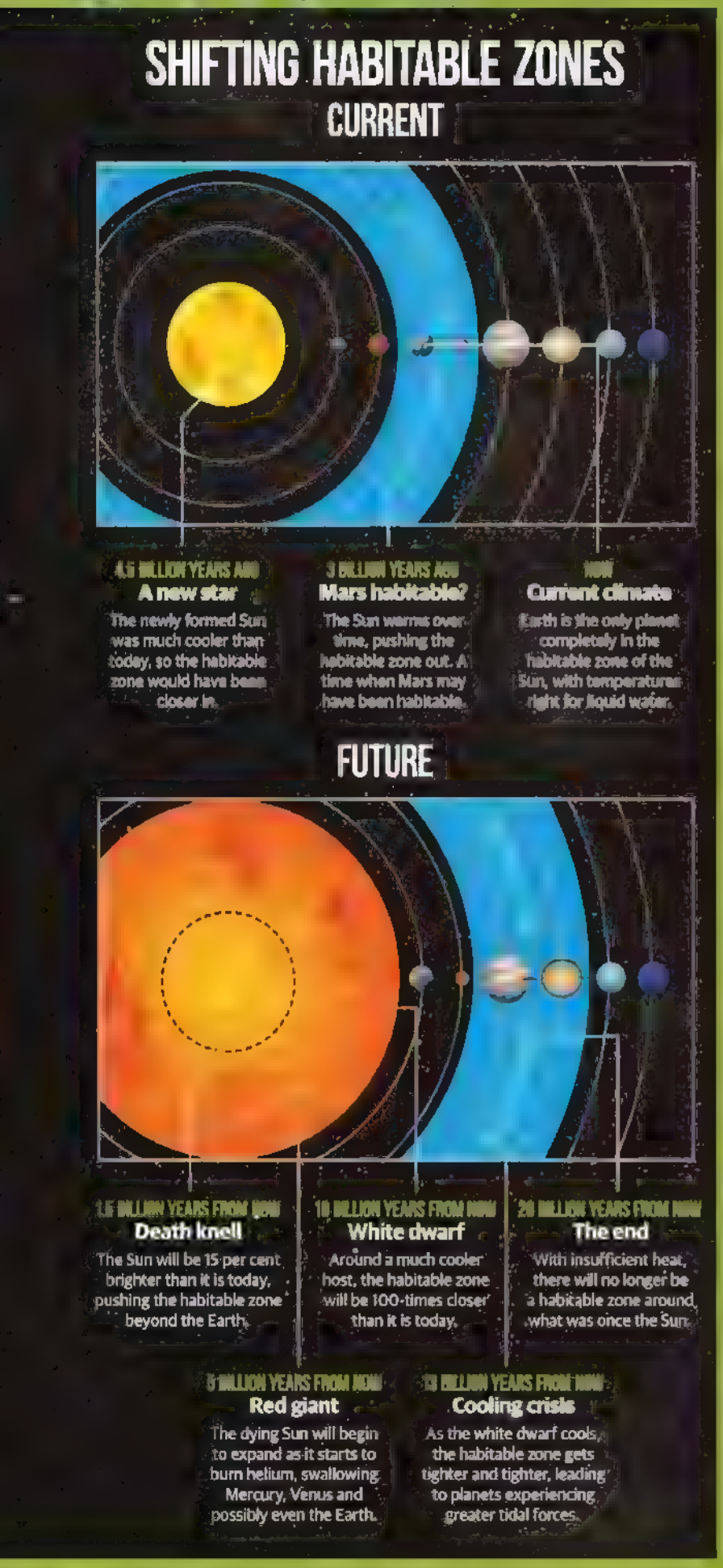
increased solar luminosity will easily spin up the asteroids to break-up speed. As a result, the main belt of asteroids will likely be pulverised into an extended debris field," Veras says. Dangers upon more dangers. "No place within the Solar System will be safe from the threat of asteroid bombardment."

Despite these existential threats, moving to another solar system is a huge undertaking. "It's like moving to another country, whereas moving elsewhere in the Solar System is like changing bedrooms," says Sutter. Gertz thinks it's just too difficult, too economically expensive. "It's not going to happen," he says. Even if some of the inhabitants of the stricken planet do manage to escape, they won't be able to evacuate everyone, so the majority of the civilisation is stuck where it is, battling to save itself against the ravages of a star in the twilight of its days. If a civilisation is already facing the death of its star, it has to be one of the oldest stars in the universe. That life would likely have been there a long time, arguably with the most mature technology of any species in the cosmos. "Major astral engineering would be required to survive, and that might be detectable," says Gertz. They may also be sending out distress signals in a last-ditch attempt at salvation. We may also have a better chance of hearing their mayday. Without as much background noise, "trying to be heard might be easier than around a normal star," says Sutter.

If their efforts are ultimately successful, they'll find themselves orbiting a white dwarf star. When stars like the Sun die they shed their outer layers into space to form a shell called a planetary nebula. At its heart is a white dwarf, an ever-cooling core of carbon and oxygen, by-products of the helium burning that saw the dying star bloat in the first place. A white dwarf is about the same size as Earth, whereas the original star was around a million times bigger. So far they've been largely overlooked as a place to search for life, but while

Source: Wikipedia commons © Martin Ballard

As the Sun brightens and bloats, Mars could become a more habitable planet for us



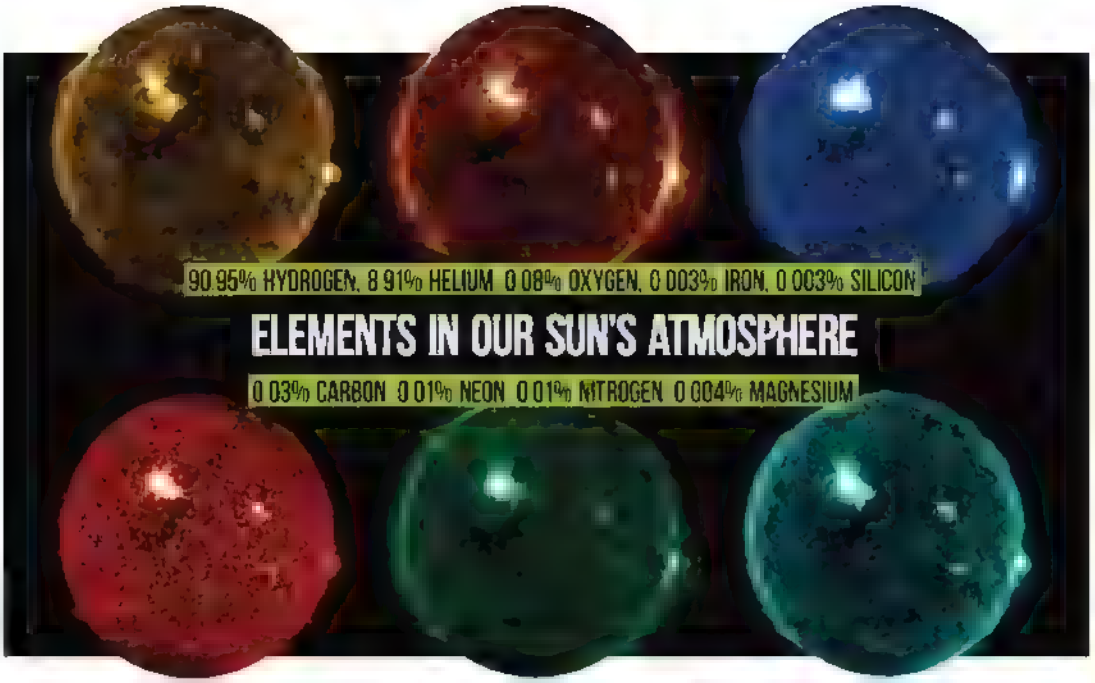
they are small in stature they are not in number. White dwarfs account for 15 per cent of all the stars in the universe, and their ranks are only set to swell. "95 per cent of stars will become white dwarfs," says Thea Kozakis, a PhD student at the Carl Sagan Institute, part of Cornell University.

Kozakis' work is focused on modelling the atmospheres of planets around white dwarfs. "A planet could stay in the habitable zone of a white dwarf longer than it could with the Sun," she says. "It's actually a pretty stable environment." We're talking about a habitable zone lasting 8.5 billion years. That could make it an ideal destination for an otherwise doomed species that could overcome the significant obstacles of moving solar systems. You certainly wouldn't have to worry about the death of your star – it's already happened. Yet Kozakis is more interested in life that emerges only after the star has transitioned into a white dwarf.

A rocky planet that initially had its atmosphere stripped away could regain one as it's pummelled by an increase in asteroid and comet activity. We already suspect such events delivered much of the water to the early Earth before life rapidly took hold. What happened here could happen there too. We already see evidence of material heading inwards and falling on white dwarf stars. "A lot of useful material is being transported towards where the habitable zone would be," says Kozakis.

Not everything would be the same though. A white dwarf is hot, but its diminutive size means it struggles to emit its heat through such a limited surface area. Consequently, the habitable zone is a hundred-times closer than the Sun's as you need to huddle closer to get the same warmth. A potentially habitable planet would orbit the white dwarf in a matter of days. "That can lead to tidal disruption," says Kozakis. This is where the difference in gravity felt between the two sides of an orbiting object leads to deformation. Like the constant squeezing of a squash ball, this injects extra energy into the planet's interior. This already happens in several places in our own Solar System, most notably on Jupiter's moon Io, where it results in intense volcanism. That's hardly conducive to a life-friendly world. "Planets around white dwarfs can avoid this if their orbit is very circular," says Kozakis. That orbital path must deviate from a circle by less than one part in a million. If that sounds like an unlikely scenario, it may not be. "Planets that migrate inwards towards a star do tend to end up on circular orbits," Kozakis says.

While a tight orbit puts any life under unusual strain, it should make such planets easier to find. One of the techniques we use to detect planets beyond our Solar System is called the 'transit method'. As a planet orbits, it can periodically pass between us and its star, causing the star to dim. This is how the Kepler space telescope found thousands of alien worlds. Yet for small Earth-like planets around big Sun-like stars, the drop in brightness is typically 0.01 per cent. Teasing these changes out of the background variation of the star



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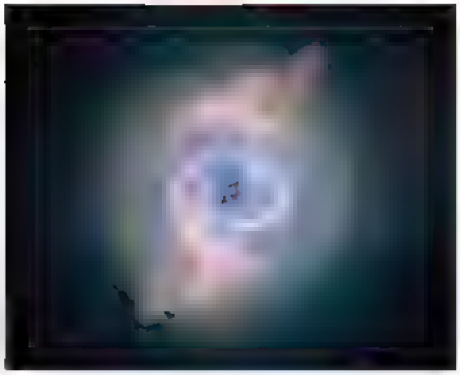

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can be a real challenge. "It may be easier with white dwarfs," says Kozakis. The small size of the dead star means that a transiting planet would block around 50 per cent of the star's light - a much more obvious effect. Normally to confirm the presence of a planet, astronomers wait for three equally spaced transits to make sure that the change in brightness really is down to an orbiting world. For an Earth-like planet you'd have to wait three years. Yet habitable planets around white dwarfs would go round in a day or two. You could see the three transits you need in a week. That said, you still need to be keen-eyed. "Each transit only lasts a minute," says Kozakis. Hubble and the upcoming James Webb Space Telescope (JWST) should be up to the job. The Transiting Exoplanet Survey Satellite (TESS), launched in April 2018, can also join the search party.

It's a great time to be contemplating life around white dwarfs. In 2013 the European Space Agency launched Gaia to chart the positions and distances of a billion stars in our Milky Way. Before 2018 only 30,000 white dwarfs had been discovered. Now, thanks to the last haul from Gaia, it's over 250,000. For the first time we're getting a concrete census of these enigmatic objects. We're also understanding how they change over time. Without a source of new heat, a white dwarf gradually cools, and the habitable zone shifts with it. An effect called white dwarf crystallisation was predicted as far back as the 1960s. As the carbon and oxygen cool, it condenses into a crystal structure. Yet this wasn't confirmed until 2019. Understanding the way a white dwarf's energy output changes as it crystallises could tell us more about how long life is able to stick around in its presence.

With all these factors considered, Kozakis says that people are starting to wake up to the idea of life around white dwarfs and are beginning to look for signs of life there. Over the past three years tentative SETI searches have also sought out signals coming from these systems. If we're serious about finding life elsewhere in the universe - arguably the biggest discovery in all of human history - then we need to keep our options open. That means looking in all the places that aliens could be hiding, not just those most similar to us. As Sutter says: "It's worth a shot."

"A PLANET COULD STAY IN THE HABITABLE ZONE OF A WHITE DWARF LONGER THAN IT COULD WITH THE SUN. IT'S PRETTY STABLE"

Above left: An example of a Sun-like star shedding its outer layers as it approaches the end

Above right: The Transiting Exoplanet Survey Satellite (TESS) being prepared prior to its launch in 2018

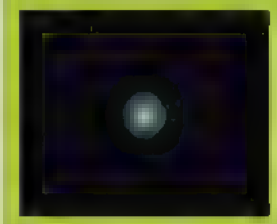
POSSIBLE CANDIDATES

The nearer the white dwarf, the easier it is to look for signs of life

SIRIUS B
8.6 LIGHT YEARS

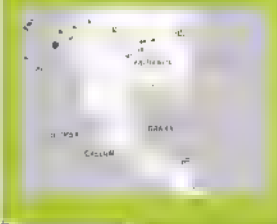
PROCYON B
11.46 LIGHT YEARS

VAN MAANEN'S STAR
14.04 LIGHT YEARS



GJ 440
15.11 LIGHT YEARS

40 ERIDANI B
16.26 LIGHT YEARS



SECRETS OF THE OCEAN WORLDS

If physics and chemistry are the same throughout the universe, is biology too?

Ocean worlds

Earth isn't the only world which accommodates water. There are moons in the Solar System half the size of Earth that hold much more. These are known as ocean worlds. Astronomers continue to scrutinise these in great detail as they have the potential to change how biology is viewed throughout the universe. "An ocean world is any planet, or sometimes moon, that has at least ten times the amount of water that Earth does. For reference, Earth is about 0.1 per cent water, so an ocean world has a water content of one per cent or greater," explains Dr Lynnae Quick, an ocean worlds planetary scientist at NASA's Goddard Space Flight Center in Maryland, to **All About Space**.

Water is a necessity for life as we know it. Every living thing on Earth consumes water to stay hydrated and survive. Water also provides opportunities for exploration, whether it is taking to the oceans to discover a new bit of land or diving into the depths below, where many mysteries remain unanswered. Astrobiologists now want to up the ante and explore the oceans of other worlds millions of miles - or possibly even light years - away in order to find signs of alien life.

How worlds end up having global oceans, either visible on the surface or buried underneath an icy exterior, is a story in itself. Water does not float through space as liquid droplets waiting to splash down on a surface. As space is so cold, water travels through space as grains of ice. As new planetary systems begin to form around a young star, water can stay as these icy grains beyond a certain radius, known as the 'ice line'.

"There is a natural ice line in the Solar System where volatile species migrated away from the centre, akin to a tree line on tall mountains. The outer Solar System is replete with water, among other such species," says Dr Chris German, a senior scientist at the Woods Hole Oceanographic Institution (WHOI) in Falmouth, Massachusetts. "Planets tend to have geothermal gradients, whether it's from the cooling of magma, the radioactive decay of long-lived isotopes or tidal heating. As you go deeper, things warm up, and the potential for melting arises.

"Of course, if the oceans get too deep, then as you dive further and further in, higher pressures arise than what we see on Earth, and compaction can lead to new and different forms of solid-phase minerals with the same water composition to form," says German. He also describes this in a way that's simpler to understand. "Some ocean worlds can be ice sandwiches."

Ocean worlds

© ESO

Right: This artist's impression shows the 'ice line' around the protostar V883 Orionis

Below: Cassini's dive through the plumes of Enceladus was a monumental occasion in terms of ocean world research

Tidal heating is a term frequently mentioned when talking about ocean worlds, but more specifically the ocean moons that orbit larger planets. The ocean moons beyond the asteroid belt include three of Jupiter's four Galilean moons – Ganymede, Callisto and Europa – as well as Saturn's moons Enceladus, Titan and Mimas and Neptune's moon Triton. The fact that they are all gravitationally bound to enormous planetary bodies means that there is consequently a gravitational sloshing effect in the moons' cores.

This sloshing effect creates heat in the form of friction within the core, which in turn heats up the outer layers. Tidal heating, when combined with radiogenic heating from radioactive decay, melts the water ice accumulated from the moons' formation beyond the ice line and creates interior oceans. When you see one of these moons and acknowledge its icy surface, remember that there is an enormous quantity of subsurface liquid water lying beneath, which astrobiologists are working incredibly hard to try and investigate.

"Ocean worlds are important to study because we can test an important hypothesis in science: biology," explains Dr Morgan Cable, a research scientist for the astrobiology and ocean worlds group at NASA's Jet Propulsion Laboratory (JPL) in Pasadena, California. "We already know that the rules of physics – the speed of light, the theory of general relativity and so on – seem to apply everywhere in the observable universe. The same is true for the rules of chemistry: those also seem to apply everywhere. But we haven't tested this for biology yet. If you have an environment with habitable conditions and you wait long enough, will life emerge?"

On 15 September 2018, NASA's Cassini mission came to an end. During its 13 years at Saturn it returned breathtaking images and invaluable data, not just about the ringed planet, but its moons too. The data returned about Enceladus was key in revitalising public attention towards ocean world research, which had been growing over the last few decades. A notable event which strengthened this shift was when the spacecraft flew through a plume of material erupting from the icy surface of Enceladus on 28 October 2015. With its instruments turned on and ready to go, Cassini dove head first into the plume, and the data taken from this encounter led to remarkable discoveries about Enceladus' interior. The most important was that within this world, 25-times smaller than Earth, lies the three main ingredients for life: liquid water, an energy source for metabolism and a tantalising selection of chemical ingredients such as carbon, nitrogen, oxygen, phosphorus and sulphur.

With this discovery, astrobiologists made an extremely compelling case that future exploration missions should look to visit more ocean worlds in the outer Solar System. This was once again strengthened when astrobiologists found something very interesting in the data collected by NASA's Dawn mission, which was operational at the dwarf planet Ceres between 2015 and 2018.

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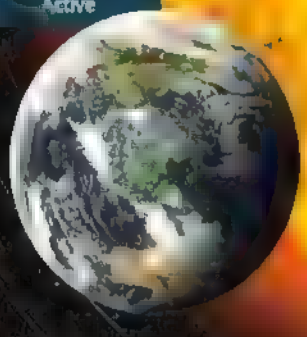
OCEAN WORLDS OF THE SOLAR SYSTEM

These bodies host their own oceans – which could be teeming with life – and they lie right on Earth's doorstep



EARTH
Size: One Earth radius
Distance from the Sun: 1 AU
Type of ocean: Active

CERES
Size: 0.08 Earth radii
Distance from the Sun: 2.8 AU
Type of ocean: Mature

GANYMEDE
Size: 0.4 Earth radii
Distance from the Sun: 5.2 AU
Type of ocean: Trapped

EUROPA
Size: 0.24 Earth radii
Distance from the Sun: 5.2 AU
Type of ocean: Possibly active

CALLISTO
Size: 0.38 Earth radii
Distance from the Sun: 5.2 AU
Type of ocean: Trapped

ENCELADUS
Size: 0.04 Earth radii
Distance from the Sun: 9.5 AU
Type of ocean: Active

MIMAS
Size: 0.03 Earth radii
Distance from the Sun: 9.5 AU
Type of ocean: Possible

TITAN
Size: 0.4 Earth radii
Distance from the Sun: 9.5 AU
Type of ocean: Trapped

TRITON
Size: 0.2 Earth radii
Distance from the Sun: 30.1 AU
Type of ocean: Possible

PLUTO
Size: 0.18 Earth radii
Distance from the Sun: 39.5 AU
Type of ocean: Possible

TYPES OF OCEAN

Active
Known active ocean with great potential for supporting life.

Mature
The body is ageing and the ocean is in the process of freezing over.

Trapped
Likely has a covering, like ice, over the ocean. Unlikely to support life.

Possible
Shows signs of an ocean, but further investigation is needed to confirm.

Possibly active
There is an ocean, but its potential to support life is currently unknown.

LARGEST OCEANS IN THE SOLAR SYSTEM

Out of all of the known ocean worlds, which one takes home the gold for the largest amount of liquid water present?

Above: Artist's impression of cryovolcanoes erupting on Europa's surface and water under its icy crust

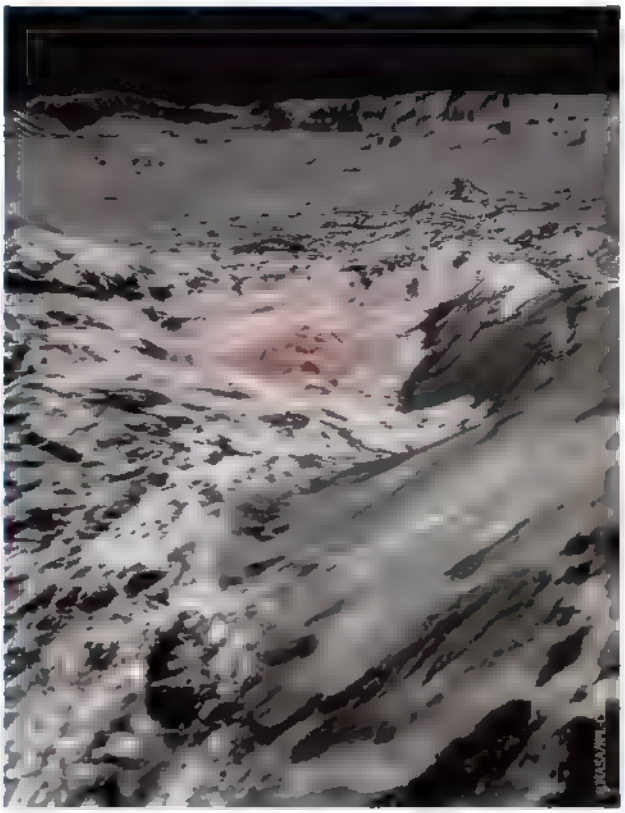
"Measurements from the Dawn mission indicate salts on the surface of Ceres, which can only be there if they are being constantly replenished from underneath. This means Ceres has activity due to brines (salty liquids), making it an 'evolved' or 'mature' ocean world," says Cable. "Based on our current understanding, only a few per cent of Ceres' subsurface ocean is left, so Ceres may serve as an excellent example of what an ocean world without tidal heating looks like at the end stages of its life when the energy runs out."

An honourable mention also goes to NASA's New Horizons mission, which returned the first close-up images of the dwarf planet Pluto from the darkest, most distant region of the Solar System, known as the Kuiper Belt. The images that were transmitted back to Earth from over 5 billion kilometres (3 billion miles) away were truly extraordinary. They revealed cracks on the surface, possible ice volcanoes and an extremely thin atmosphere made up mostly of molecular nitrogen. These are all lines of evidence that could point towards a subsurface ocean that is replenishing the dwarf planet's atmosphere via the eruption of ice volcanoes or immediate evaporation after escaping through surface cracks.

When looking at these ocean worlds and the data collected from their respective exploration missions, it's understandable that astrobiologists can't wait for the next mission to launch and reveal a brand-new host of discoveries. Two missions due to launch within the next decade are NASA's Europa Clipper mission, due to explore Jupiter's moon Europa sometime in the 2020s, and the European Space Agency's (ESA) JUpiter ICy moons Explorer (JUICE), due to arrive at Jupiter in 2029.

These two bespoke moon missions aim to provide a thorough reconnaissance of the three watery Galilean moons, and will look to fully characterise their current states and compositions while also informing us about their evolution over the last 4.6 billion years. Europa is roughly 90 per cent the size of Earth's Moon, but holds twice as much water than all of Earth's oceans combined. The astrobiological processes that may exist in this moon could answer the age-old question, is

Below: This false-colour image highlights salty liquids that have recently risen from the subsurface ocean



there life elsewhere in the universe? And if Europa doesn't host life, does it at least have a habitable and hospitable environment for it?

"If we can find evidence in the outer Solar System that would imply a second origin of life here in our corner of the universe," says German. "Occam's razor then suggests that life should be pervasive in every other star system and we're not that special at all."

There are even efforts underway to test how we could explore these subsurface oceans directly. In 2019 a team of engineers from NASA's JPL travelled to Antarctica to test the Buoyant Rover for Under Ice Exploration (BRUIE), a roving vehicle built with the long-term goal of exploring the subsurface oceans of icy moons.

BRUIE uses a unique combination of buoyancy and wheels with tiny spikes in them to move along the underside of ice sheets. This rover would be able to provide direct measurements of an ocean's water salinity, dissolved oxygen levels, temperature and pressure. Who knows, one day in the future there could be a new documentary series talking about the oceans of Europa and what ocean life is swimming around in there!

> "CERES MAY SERVE AS AN EXCELLENT EXAMPLE OF WHAT AN OCEAN WORLD WITHOUT TIDAL HEATING LOOKS LIKE AT THE END STAGES OF ITS LIFE" MORGAN BAY

Looking beyond our own Solar System, there are many exciting opportunities for discovering ocean worlds in other stellar systems. Unfortunately these are a little bit harder to detect, but there are still techniques that can be used to infer their existence. "We can identify ocean worlds in extrasolar planetary systems based on their size and inferred density," says Quick. "Low-density, low-mass planets are likely to be ocean worlds."

A simple technique that is commonly used in astronomy when it comes to aiding

POTENTIAL OCEAN WORLDS OUTSIDE THE SOLAR SYSTEM

Planets in the TRAPPIST-1 system

The popular TRAPPIST-1 system – with its seven Earth-sized planets – became even more popular in 2017 when astronomers announced that they could be harbouring liquid water. Three of the planets reside in the star's habitable zone, suggesting they would be the most likely objects of interest.

GJ 1214 b

GJ 1214 b is considered a super-Earth: it is 2.7 times Earth's radius. It's thought it could be surrounded in a steamy atmosphere. This potential ocean world was first discovered in 2009, but research has revealed that the exoplanet's density is closer to water as opposed to Earth's rocky density, which is much greater.

Kepler-22b

This exotic exoplanet has been described by NASA as a "super-Earth that could be covered in a super ocean". This remark is based on the fact that this planet, which is 2.4-times larger than Earth, resides in the habitable zone around a star very similar to the Sun. This implies that it could have a similar evolutionary history to Earth.

Kepler-62f

Located 1,207 light years away in the constellation Lyra, Kepler-62f is a planet 40 per cent larger than Earth and sits in the habitable zone of its host star. A 2016 study of Kepler-62f found that there are multiple atmospheric compositions that allow it to stay warm enough to sustain liquid water.

THE FUTURE OF OCEAN WORLD EXPLORATION

These robotic explorers could provide vital evidence to answer astrobiology's greatest questions

1 EUROPA CLIPPER

NASA's next mission beyond the orbit of Mars is the Europa Clipper, succeeding the Juno mission currently at Jupiter. The mission is scheduled to launch in the mid-2020s. The spacecraft will carry nine scientific instruments, each built for a specific purpose, and will conduct a full scan of the surface. It will also utilise ice-penetrating equipment in order to characterise Europa's subsurface ocean.

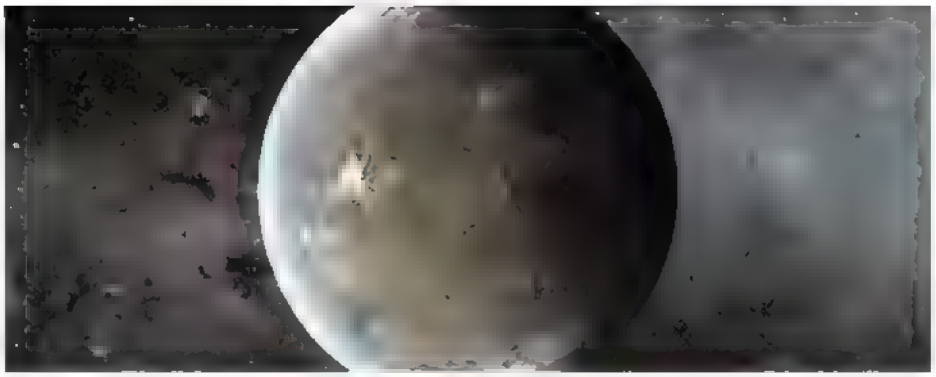
2 JUICE

The European Space Agency has also taken a particular interest in the Galilean moons and looks to visit three of them during its three-and-a-half-year stay. It will arrive at the Jovian system in 2029 and investigate each moon's environment and the relationship between the three. However, particular emphasis will be on Ganymede.

3 BRUIE

Although this mission is unlikely to see extraterrestrial exploration within the current decade, it has already been tested in Earth's best analogue location: Antarctica. The buoyancy and manoeuvrability of the Buoyant Rover for Under-Ice Exploration vehicle represents a unique and feasible method of gaining direct insight into subsurface oceans.

"AN OCEAN WORLD IS ANY PLANET, OR SOMETIMES MOON, THAT HAS AT LEAST TEN TIMES THE AMOUNT OF WATER THAT EARTH DOES"



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research regarding an exoplanet's potential for accommodating liquid water is calculating if a planet resides in its host star's habitable zone. This is the radius range around a host star where the temperature is perfect for water to exist as a liquid. If the planet orbited any closer the water would evaporate, but if the planet was too far away the water would freeze into ice.

This basic technique is used by astrobiologists when determining if an exoplanet could host liquid water as it's known that Earth resides in the Sun's habitable zone. It's important to remember that this is an extreme simplification and does not take into account things such as a planet's composition, atmosphere, evolution history and so much more.

To make a discovery of this calibre with great confidence and little uncertainty, the techniques that astrobiologists and astronomers use to detect exoplanets and analyse them will need to be improved in order to infer other aspects of a planet's properties - this includes its atmosphere. "Astronomers can further their techniques by improving spectral resolution and sensitivity," says Cable. "This would help us identify possible biosignature molecules in the atmospheres or on the surfaces of exoplanets."

Recent research suggests that the Milky Way could be littered with ocean worlds. A study led by Quick suggests that out of the 53 exoplanets surveyed, at least 30 of them could be ocean worlds, as they fit the assumed parameters. This is based on restricted knowledge, however, as current technologies and techniques allow astronomers to definitively measure an exoplanet's size, mass and distance from the host star, which can only imply a planet's surface temperature. "If we see that a planet's density is lower than Earth's, that's an indication that there might be more water there and not as much rock and iron," Quick says. "But if a planet's surface temperature is less than 32 degrees Fahrenheit [0 degrees Celsius] where water is frozen, then we have an icy ocean world and the densities for those planets are even lower."

With the number of known exoplanets currently over 4,000, Quick's results could be extrapolated, suggesting that there are thousands of ocean worlds dotted across the Milky Way. Quick also makes the point that there could be other signature signals of ocean worlds that are currently unknown, and that upcoming missions, for example the Europa Clipper mission, will identify these signals.

This could then be applied to exoplanet research in order to identify even more ocean worlds. This could provide greater reliability and accuracy about whether an exoplanet is an ocean world, since it provides something more meaningful than just inferring information based on the planet's size, mass and density.

Even the recent news regarding Ceres likely being a more mature ocean world could give astronomers new signs and biosignatures to look out for when investigating exoplanets. The study of ocean worlds, both within our Solar System and elsewhere in the cosmos, is certainly one to keep a keen eye on. Through upcoming missions astrobiologists will become even more equipped with highly precise data that could answer one of the most profound questions there is, finally revealing if life on Earth is special or not.

© NASA/JPL

Above: Kepler-62f has the potential to be an ocean world, but it is far from confirmed as of yet

Left: Jupiter next to its four Galilean moons. From top to bottom: Io, Europa, Ganymede and Callisto

Staff Writer
Lee holds a degree in observational astronomy which has given him the knowledge to discuss the latest complexities of the universe

SPACE, SATELLITES AND SELF-ISOLATION

THE ASTRONOMICAL IMPACT OF COVID-19

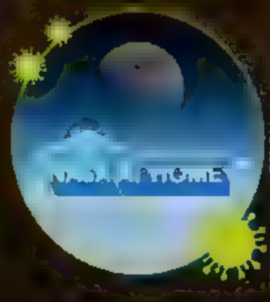
Coronavirus has had seismic effects on all aspects of life globally, but what has the space industry been able to tell us, and what can it do to help?

Reported by Lee Cavendish

FIVE WAYS TO PASS THE TIME IN ISOLATION

1 NASA at Home

On the NASA homepage – nasa.gov – the US space agency has set up its #NASAatHome activities page. This new and interactive subsection of the NASA website offers a range of offerings to engage the whole family. There are podcasts, videos, projects and even virtual- and augmented-reality tours that will bring the universe to anyone's home.



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The world is in the midst of an unprecedented pandemic, and it is having a profound effect on individuals, businesses and industries across the globe. Since COVID-19 – also known as 'coronavirus' – gained global attention at the beginning of 2020, it has had a knock-on effect that can even be seen from space.

In response to battling the virus, almost all the world's governments have issued strict lockdown policies stating that people can only leave their homes for essential shopping and going to work – but only for key workers. This has led to a dramatic reduction in travel, with local non-essential businesses being asked to close their doors temporarily and public gatherings being postponed.

The harmful emissions that usually permeate the atmosphere above busy cities have shown signs of clearing as a consequence of these closures. Although COVID-19 is a negative situation as a whole, the side effects it has been having on the planet's atmosphere and the environment are a minor positive. Calls for a large-scale reduction of fossil-fuel burning and other means of harmful emission production have intensified over the last few years, and in the midst of this pandemic satellites in low-Earth orbit have been able to see what fossil-fuel abstinence can do for our planet.

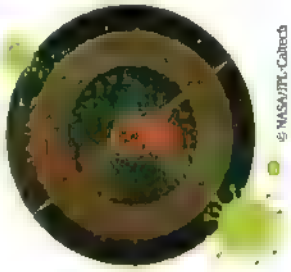
The European Space Agency (ESA) has a fleet of satellites dedicated to observing Earth from space and noting any changes that occur. This all falls under the space agency's Copernicus Programme. Named after the famous Polish astronomer who first suggested that Earth revolves around the Sun, this satellite suite namesake was created to manage the environment and understand the influence of climate change. One particular member of the Copernicus family, known as a Sentinel, has been observing the concentration of nitrogen dioxide over the globe, which is directly linked to the severity of air pollution.

Wuhan, a city in the Chinese province of Hubei, is largely regarded as the global epicentre of the COVID-19 outbreak, meaning that China was the first country to exhibit strict lockdown protocols. Over the course of December 2019 and January, February and March 2020, the Copernicus Sentinel-5P satellite provided timely updates on the concentration of nitrogen dioxide, which is usually released via power plants, vehicles and industrial facilities. When the team put together images taken over the course of three months, a dramatic reduction in the molecule's concentration over the entire country was shown, most noticeably above Beijing and Shanghai. These two cities are almost synonymous with air pollution and bad air quality. They are hugely populated cities in a country where it was reported in 2012 that air pollution was responsible for over a million deaths. To have such a drastic drop in these emissions could actually save some lives, and at the very least provide better air quality for a better quality of living.

© NASA

As the virus began rearing its head in Europe, Italy had the initial outbreak and experienced the harshest consequences of it first. As a result the ESA satellites began monitoring Italy, and the Sentinel-5P satellite provided ten-day average frames of the concentration of nitrogen dioxide from January to March 2020. "The decline in nitrogen dioxide concentration over the Po Valley in northern Italy is particularly evident," states Claus Zehner, the ESA's Copernicus Sentinel-5P mission manager. "Although there could be slight variations in the data due to cloud cover and changing weather, we are very confident that the reduction in concentration that we can see coincides with the lockdown in Italy causing less traffic and industrial activities."

In early March Italian Prime Minister Giuseppe Conte enforced harsh measures in the northern region that saw a quarter of the population have their movements restricted. Cities such as Milan



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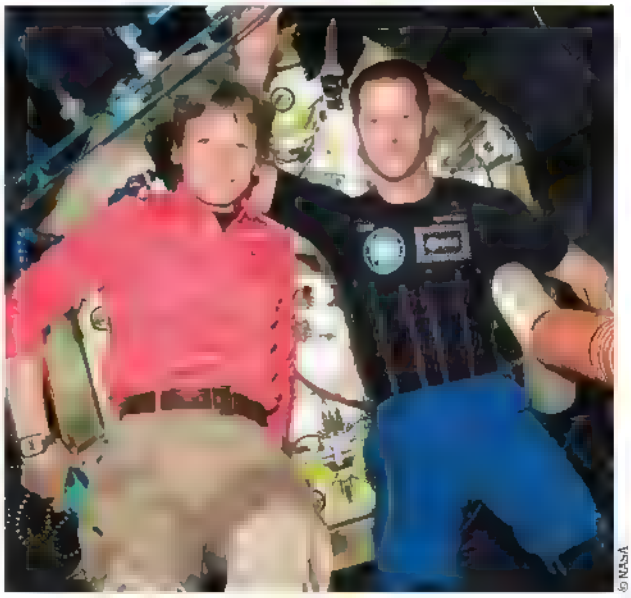

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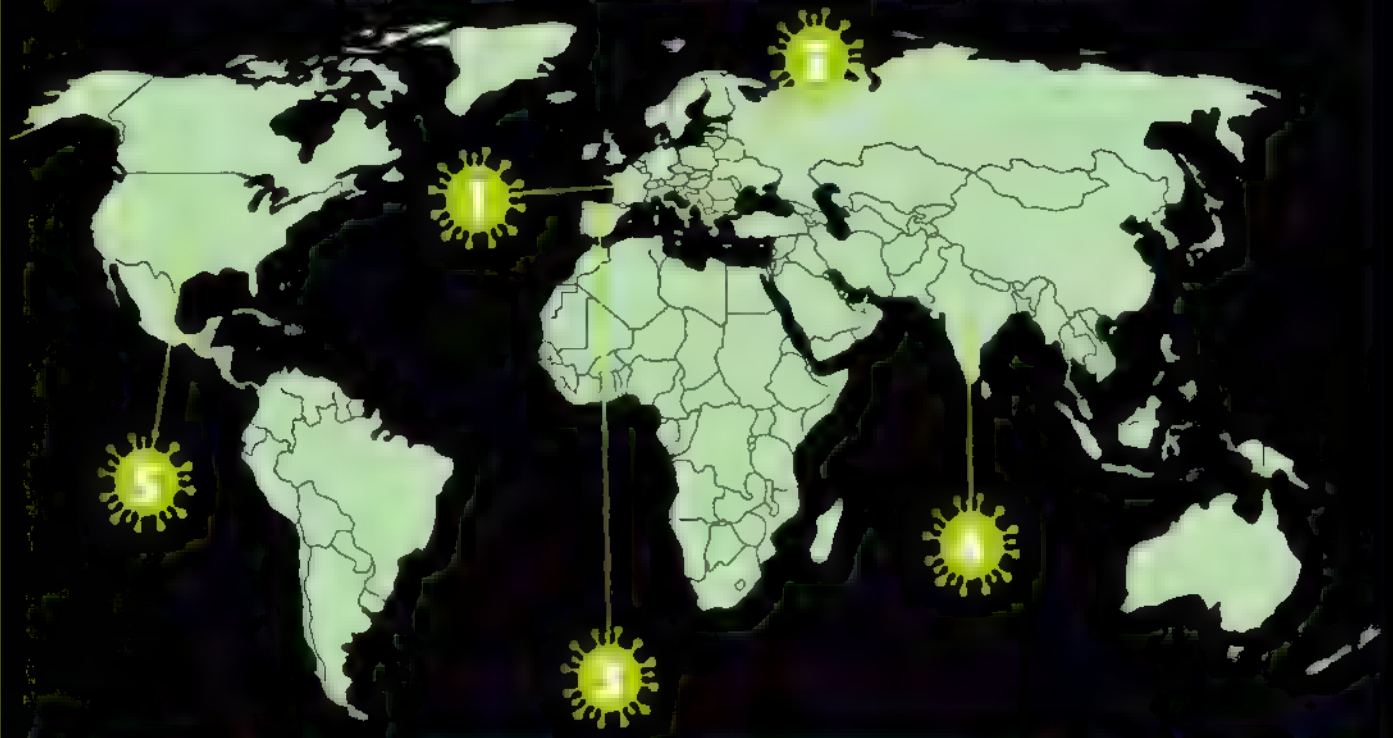
Above: NASA can't risk sending all workers home as astronauts aboard the ISS rely upon constant communication.

Right: Peggy Whitson (left) and Thomas Pesquet (right) were both on the ISS for Expeditions 50 and 51.

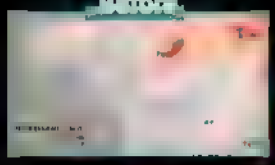
BEFORE AND AFTER:

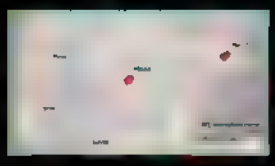
AIR-POLLUTANT LEVELS AFTER ISOLATION

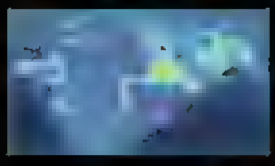
These images, courtesy of ESA's Copernicus Programme and NASA's Aura satellite, show the drastic improvement in air quality as a consequence of a global lockdown

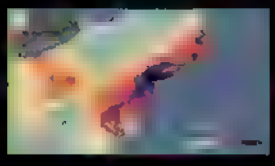


Before









1. France

The majority of France doesn't usually experience high levels of nitrogen dioxide in its atmosphere, the expected exceptions being Paris, Lyon, Marseille and Lille. Paris has experienced an approximate 54 per cent drop in air pollutants compared to previous years.

2. Italy

Italy was the first country in Europe to be hit hard by coronavirus, with a lockdown put into place in response to try and slow the spread. The northern region is normally heavily polluted, as shown in the large dark-red patches. In March 2020 Milan showed an approximate 47 per cent drop.

3. Spain

Spain was arguably the second country in Europe to feel the worst effects of the virus, and as a result was put under extremely intense lockdown conditions. This lockdown has led to a 48 per cent reduction in air pollutants in the Spanish capital of Madrid.

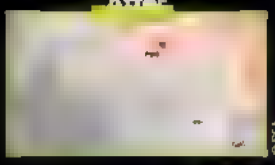
4. India

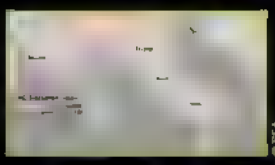
After the Indian government put over a billion people in lockdown in late-March, the country has experienced a dramatic and rapid reduction in nitrogen dioxide. In fact, compared to the average levels of January to March 2020, cities such as Mumbai and Delhi have experienced a drop of between 40 and 50 per cent.

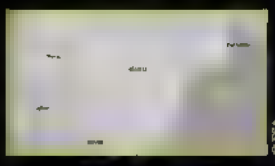
5. United States

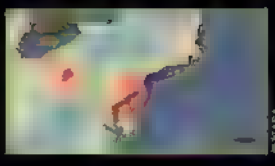
The United States' northeastern coast houses some of its busiest cities, such as New York, Boston, Philadelphia and Washington, D.C.. The average nitrogen dioxide emission from March 2015 to 2019 has been very high. As expected, measurements from March 2020 have shown a massive 30 per cent reduction.

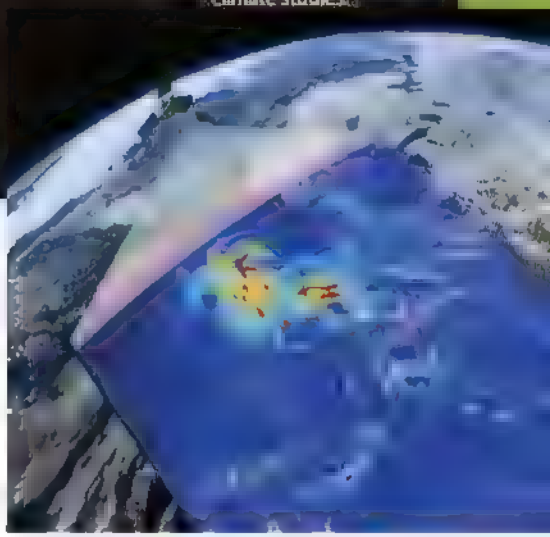
After



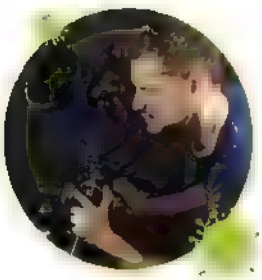








Right: Sentinel-5P has delivered valuable high-precision data about Earth's atmosphere



Venice, Turin and others are thought of as the economical heart of the country, so to have such firm restrictions in place obviously took its toll. However, these restrictions consequently saw a reduction in nitrogen dioxide. Not only that, but in Spring, the waters of Venice appeared to be returning to their former unpolluted beauty.

Venice 'the floating city', is a beautiful place to visit, but because of this it's a tourist hotbed. Tourist demand in recent years has led to more boat traffic and pollutants being released into the city's majestic canals. Another member of the Copernicus Programme, Sentinel-2, revealed the difference in water quality between 13 April 2019 and 19 April 2020, and the contrast is incredible. The obvious murky discharge from overtourism has faded. The waters appear clearer, and nature is returning.

At the time of writing the latest results from the Copernicus Programme show that four major European cities – Milan, Rome, Paris and Madrid – all exhibit much less air-pollutant concentrations compared to the previous year. Decreases average out to 50 per cent less than the previous year, with Paris showing the greatest reduction with 54 per cent. However this is still scientific observation, and uncertainty needs to be taken into account - to the tune of 15 per cent for these calculations. Nevertheless, the lowest average is still a 35 per cent reduction of air pollutants, which is an incredible feat for humankind in some of the most industrially demanding cities of the world.

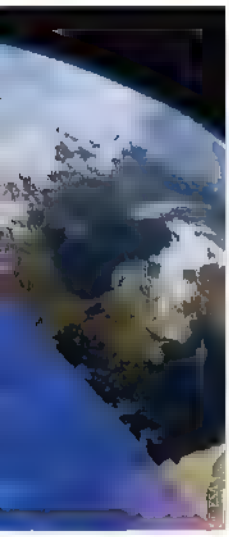
NASA also has its own set of eyes from above with satellites that contribute to the space agency's Earth Observing System (EOS). The two satellites in focus, Aura and Terra, have likewise been monitoring air pollution in the form of nitrogen dioxide and aerosols respectively. The results from the Aura satellite show that the northeastern

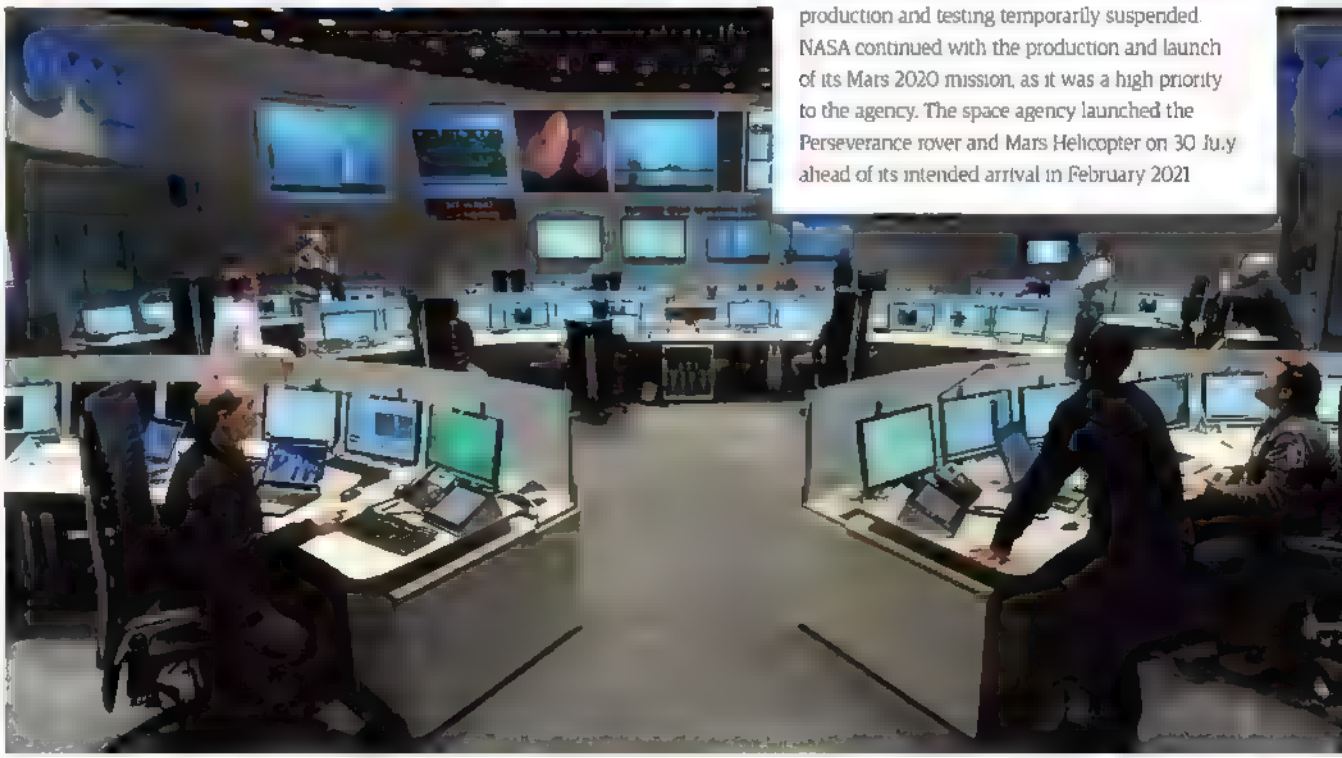
region of the US had a 30 per cent lower average concentration of nitrogen dioxide when compared to the averages in March 2015 to 2019. Its partner, Terra, has been keeping an eye on India since the strict lockdown of 1.3 billion people on 25 March 2020. Remarkably in less than a month's time NASA's satellite had measured a 20-year record low in aerosol levels over the country.

While space agencies continue to carefully monitor the data collected by these Earth-observing satellites, the same agencies have had to carefully manage the operations of space science probes elsewhere in the Solar System. NASA, the ESA and other space agencies have not been exempt from the stern recommendations to work from home where possible. As staff cannot take a whole command centre home to operate a spacecraft on another planet, a few missions have had to be put into hibernation due to these staff restrictions and work from home orders.

On 25 March 2020 the ESA made the decision to put four of its missions on 'temporary standby' – thus suspending all scientific operations – due to staffing restrictions at the European Space Operations Centre (ESOC) in Darmstadt, Germany. The four-satellite Cluster mission, the ExoMars Trace Gas Orbiter, the Mars Express orbiter and the recently launched Solar Orbiter had their scientific operations suspended until 5 April. Although this was a short period of time, it still demonstrates the gravity of the situation and the extent to which space agencies have prioritised the health of staff. The highly anticipated Rosalind Franklin rover, which is the next instalment in the European and Russian Martian astrobiology mission, has had its launch pushed back until 2022, but this was due more to technical difficulties as opposed to a COVID-related knock-on effect.

NASA had a big scare back on 23 March when an employee from NASA's Kennedy Space Center in Florida tested positive for coronavirus. However, three days prior to this announcement NASA issued a statement outlining that employees will be working from home unless absolutely necessary and will continue to support mission-essential operations for all spacecraft. However, this has meant that projects in the pipeline – such as the James Webb Space Telescope, the Space Launch System rocket and Orion spacecraft – have had their production and testing temporarily suspended. NASA continued with the production and launch of its Mars 2020 mission, as it was a high priority to the agency. The space agency launched the Perseverance rover and Mars Helicopter on 30 July ahead of its intended arrival in February 2021.





Above: NASA went ahead with launching its Mars 2020 mission on 30 July 2020

Right: The Main Control Room at the ESA's Space Operations Centre communicates with spacecraft throughout the Solar System

Meanwhile, as space agencies across the world look to juggle their obligations to build, launch and maintain spacecraft with minimal in-situ staff, they are continuing business on board the International Space Station (ISS) as normal. Although there are precautions in place to make sure the virus does not find its way onto the station, the astronaut launches and returns are happening as originally planned, with no delays.

In this current and uncertain climate astronauts can provide a service that is just as valuable as the work they do in low Earth orbit. In fact, if there is a group of people who know how to be confined in a small space for months on end, away from their loved ones, it's astronauts. Because of this expertise with isolation, astronauts have been explaining how quarantining with your family echoes living on the ISS and have been sharing what tips they have for people who are struggling.

In an interview with the United States news show *CBS This Morning*, retired NASA astronaut Peggy Whitson - who in 2017 broke the record for most cumulative days in space with a whopping total of 665 days, 22 hours and 22 minutes - spoke about effective communication. "[Self-isolation is] actually very doable, but it's very important to be able to interact well with the people you're staying with, living with."

"THE REDUCTION IN CONCENTRATION COINCIDES WITH THE LOCKDOWN CAUSING LESS TRAFFIC AND INDUSTRIAL ACTIVITIES" CLAUS ZEHNER

The ESA also released a video in March 2020 with French astronaut Thomas Pesquet's tips for social distancing. As a bit of light-hearted fun, he suggested keeping yourself occupied with tasks such as going through old photos taken on the ISS, reading some of the classics and sleeping in a vertical sleeping bag suspended from the coat hook of a door. In all seriousness, however, Pesquet stated that there are three key points to remember during this COVID-19 outbreak. Firstly, always listen to the instructions of health professionals. Secondly, wash your hands and do so for more than 20 seconds, consistently and thoroughly. Finally - and perhaps with the most emphasis of all - stay at home, and don't get too close to other people.

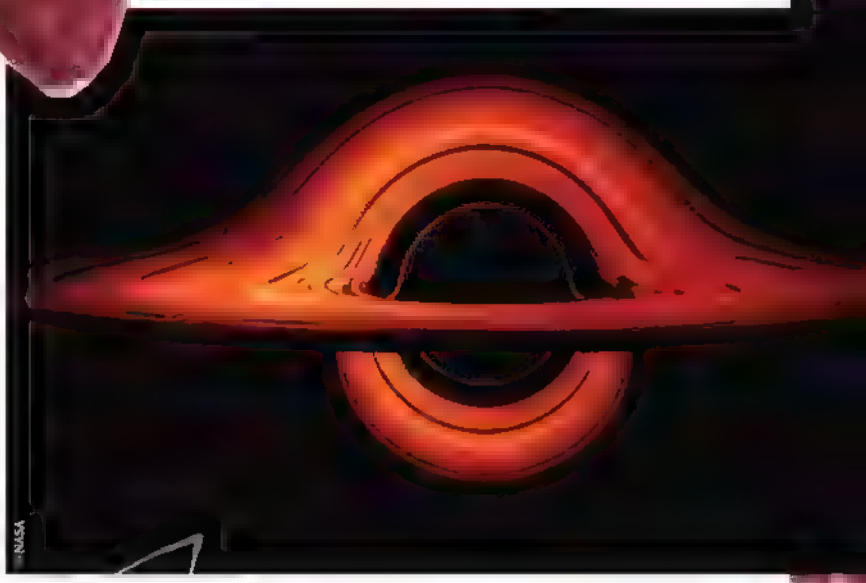
© NASA

NASA has an incredible fleet of satellites for monitoring environmental changes on Earth

© NASA

IS THIS THE END OF SPACE AND TIME?

To better understand the universe we may need to kill off Einstein's long-standing theory



As in history, revolutions are the lifeblood of science. Bubbling undercurrents of disquiet boil over until a new regime emerges to seize power. Then attention turns to toppling the new ruler. The king is dead, long live the king. This has happened many times in the history of physics and astronomy. First we thought the Earth was at the centre of the Solar System – an idea that stood for over a thousand years. Then Copernicus stuck his neck out to say we are just another planet orbiting the Sun. Despite much initial opposition, the old geocentric picture buckled under the weight of evidence from the newly invented telescope.

Then Newton came along to explain that gravity is why the planets orbit the Sun. He said all objects with mass have a gravitational attraction towards each other. According to his ideas we orbit the Sun because it is pulling on us, and the Moon orbits Earth because we are pulling on it. Newton ruled for two-and-a-half centuries before Albert Einstein turned up in 1915 to usurp him with his general theory of relativity. This new picture neatly explained inconsistencies in Mercury's orbit, and was famously confirmed by observations of a solar eclipse off the coast of Africa in 1919.

Instead of a pull, Einstein saw gravity as the result of curved space. He said that all objects in the universe sit in a smooth, four-dimensional fabric called space-time. Massive objects such as the Sun warp the space-time around them, and so Earth's orbit is simply the result of our planet following this curvature. To us that looks like a Newtonian gravitational pull. This space-time picture has now been on the throne for over 100 years and has so far vanquished all pretenders to its crown. The discovery of gravitational waves in 2015 was a decisive victory, but like its predecessors, it too might be about to fall. That's because it is fundamentally incompatible with quantum theory.

The quantum world is notoriously weird. Single particles can be in two places at once, for example. Only by making an observation do we force it to 'choose'. Before an observation we can only assign probabilities to the likely outcomes. In the 1930s Erwin Schrödinger devised a famous way to expose how perverse this idea is. He imagined a cat in a sealed box accompanied by a vial of poison attached to a hammer. The hammer is hooked up to a device that measures the quantum state of a particle. Whether or not the hammer smashes the vial and kills the cat hinges on that measurement, but quantum physics says that until such a measurement is made the particle is simultaneously in both states, which means the vial is both broken and unbroken and the cat is alive and dead.

Such a picture cannot be reconciled with a smooth, continuous fabric of space-time. "A gravitational field cannot be in two places at once," says Sabine Hossenfelder, a theoretical physicist at the Frankfurt Institute for Advanced Studies. According to Einstein, space-time is warped by matter and energy, but quantum physics says matter and energy exist in multiple states simultaneously – they can be both here and over there. "So where is the gravitational field?" asks Hossenfelder. "Nobody has an answer to that question. It's kind of embarrassing," she says.

Try and use general relativity and quantum theory together and it doesn't work. "Above a certain energy you get probabilities that are larger than one," says Hossenfelder. One is the highest probability possible – it means an outcome is certain. You can't be more certain than certain. Equally, calculations sometimes give you the answer infinity, which has no real physical meaning. The two theories are therefore mathematically inconsistent. So, like many monarchs throughout

Above: Black holes bend space and time with their great masses

Below: Newton came up with his ideas on gravity after seeing an apple fall

Above: You'd need a machine 1,000 trillion-times more powerful than the LHC to probe the Planck scale

Right: Einstein dispensed with the Newtonian picture of gravity as a force, replacing it with space-time

history, physicists are seeking a marriage between rival factions to secure peace. They're searching for a theory of quantum gravity - the ultimate diplomatic exercise in getting these two rivals to share the throne. This has seen theorists turn to some outlandish possibilities.

Arguably the most famous is string theory. It's the idea that subatomic particles such as electrons and quarks are made from tiny vibrating strings. Just as you can play strings on a musical instrument to create different notes, string theorists argue that different combinations of strings create different particles. The attraction of the theory is that it can reconcile general relativity and quantum physics, at least on paper. However, to pull that particular rabbit out of the hat, the strings have to vibrate across eleven dimensions - seven more than the four in Einstein's space-time fabric. As yet there is no experimental evidence that these extra dimensions really exist. "It might be interesting mathematics, but whether it describes the space-time in which we live, we don't really know until there is an experiment," says Jorma Louko from the University of Nottingham.

Other physicists have turned to an alternative called loop quantum gravity (LQG). They can get

"IF WE UNDERSTAND THE QUANTUM STRUCTURE OF SPACE-TIME BETTER, THAT WILL HAVE AN IMPACT ON FUTURE TECHNOLOGIES"

the two theories to play nicely if they do away with one of the central tenets of general relativity that space-time is a smooth, continuous fabric. Instead, they argue, space-time is made up of a series of interwoven loops - it has structure at the smallest scales. This is a bit like a length of cloth. At first glance it looks like one smooth fabric. Look closely, however, and you'll see it is really made of a network of stitches. Alternatively, think of it like a photograph on a computer screen: zoom in and you'll see it is really made of individual pixels.

The trouble is that when LQG physicists say small, they mean really small. These defects in space-time would only be apparent on the level of the Planck scale - around a trillionth of a trillionth of a trillionth of a metre. That's so tiny that there would be more loops in a cubic centimetre of space

Source: Wikipedia Commons/ Public Domain

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Below: Einstein's work struggles to explain how two entangled particles seemingly communicate faster than the speed of light

WHY CAN'T RELATIVITY AND QUANTUM MECHANICS GET ALONG?

QUANTUM MECHANICS

Particles are waves and waves are particles

This wave-particle duality is central to quantum physics. Light can be thought of as being made of particles called photons, or as a propagating electromagnetic wave.

All properties are 'quantised'

Values in quantum physics are a bit like shoes – they only come in set sizes. Physicists call these 'quanta'. An electron, for example, can only orbit the atomic nucleus in a limited number of configurations.

Objects exist in many states at once

Physicists say electrons exist in a 'superposition' of states. It's not in a definite state until we measure it, and beforehand we can only assign probabilities to the likely outcome.

Non-locality: spooky action at distance

Take a pair of entangled particles, change the properties of one and the other will change instantly. Einstein called this 'spooky action at distance' and was deeply disturbed by it.

WHY THEY DON'T AGREE

Gravitational fields can't be a superposition

You often get the answer 'infinity'

Gravity doesn't have a [illegible]

You get probabilities higher than one

GENERAL RELATIVITY

The speed of light is sacrosanct

Nothing can travel through space faster than the speed of light, yet entangled particles appear to defy this rule. As of yet there is no agreed explanation for this phenomenon.

Space and time are space-time

The three dimensions of space and one of time that we experience are really wrapped up together in a four-dimensional fabric called space-time. This fabric is smooth and continuous.

Gravity is geometry

Newton was wrong – gravity isn't a pull from a massive object. Instead it is the effect we see of bodies following a curved path through space-time as the result of a massive object warping it.

Acceleration and gravity

The equivalence principle says you cannot distinguish between a gravitational pull and an acceleration. Accelerate through space and you'll experience the same 'gravity' as on Earth.

than cubic centimetres in the entire observable universe. "If space-time only differs on the Planck scale then this would be difficult to test in any particle accelerator," says Louko. You'd need an atom smasher 1,000 trillion-times more powerful than the Large Hadron Collider (LHC) at CERN. How can you detect space-time defects that small? The answer is to look across a large area of space.

Light arriving here from the furthest reaches of the universe has travelled through billions of light years of space-time along the way. While the effect of each space-time defect would be tiny, over those distances interactions with multiple defects might well add up to a potentially observable effect. For the last decade astronomers have been using light from far-off gamma-ray bursts to look for evidence. These cosmic flashes are the result of massive stars collapsing at the ends of their lives, and there is something about these distant detonations we currently cannot explain. "Their spectrum has a systematic distortion to it," says Hossenfelder. But no one knows if that is something that happens on the way here or if it's something to do with the source of the bursts themselves. The jury is still out.

To make progress we might have to go a step further than saying space-time isn't the smooth,

WHAT DO WE KNOW ABOUT SPACE-TIME?

1 The Big Bang
According to general relativity, space-time began in a singularity 13.8 billion years ago. It has been expanding ever since.

2 The first light
380,000 years after the Big Bang, space-time had cooled enough for atoms to form, and light that had previously been trapped flooded the universe.

3 The first stars
After 100 to 200 million years, slightly denser regions of space-time collapsed to form the first stars. Incredibly massive, they lived fast and died young.

4 The first galaxies
Around a billion years after the Big Bang, stars clustered into dense regions of space-time which drew in even more material to make the first galaxies.

HISTORY OF SPACE-TIME THEORIES

100 CE
The Ptolemaic model
Claudius Ptolemy creates a model with Earth at the centre of creation with the Sun, Moon and planets orbiting around us. There's no explanation of why they behave that way.

1543
Copernicus publishes his heliocentric model
Polish mathematician Nicolaus Copernicus argues that the Sun is in the centre of the Solar System. His book *De revolutionibus orbium coelestium* is one of the most important scientific texts of all time.

1687
Newton's book *Principia* is published
In his landmark work Newton sets out his law of universal gravitation. All masses attract all other masses in space with a force related to the distance between them.

1803
John Dalton proposes indivisible atoms
The English chemist says that all matter is made up of tiny, unbreakable and indestructible building blocks called atoms. He was able to successfully explain a lot of chemistry using this idea.

GENERAL RELATIVITY EXPLAINED

Free fall and floating

Einstein realised that free-falling because of gravity is the same as floating with no gravity. He concluded that gravity cannot be a force, as Newton had said.

Gravity and acceleration

Accelerating in a vehicle pushes you into your seat. Gravity and acceleration feel the same, so they have the same cause: a curved path through space-time.

The bending of light

Light from a torch would appear to bend as you accelerate. Acceleration is the same as curved space-time, so light should also be bent by it.

continuous fabric Einstein suggested. According to Einstein, space-time is like a stage that remains in place whether actors are treading its boards or not - even if there were no stars or planets dancing around, space-time would still be there. However, physicists Laurent Freidel, Robert Leigh and Djordje Minic think that this picture is holding us back. They believe space-time doesn't exist independently of the objects in it. Space-time is defined by the way objects interact. That would make space-time an artefact of the quantum world itself, not something to be combined with it. "It may sound kooky," says Minic, "but it is a very precise way of approaching the problem."

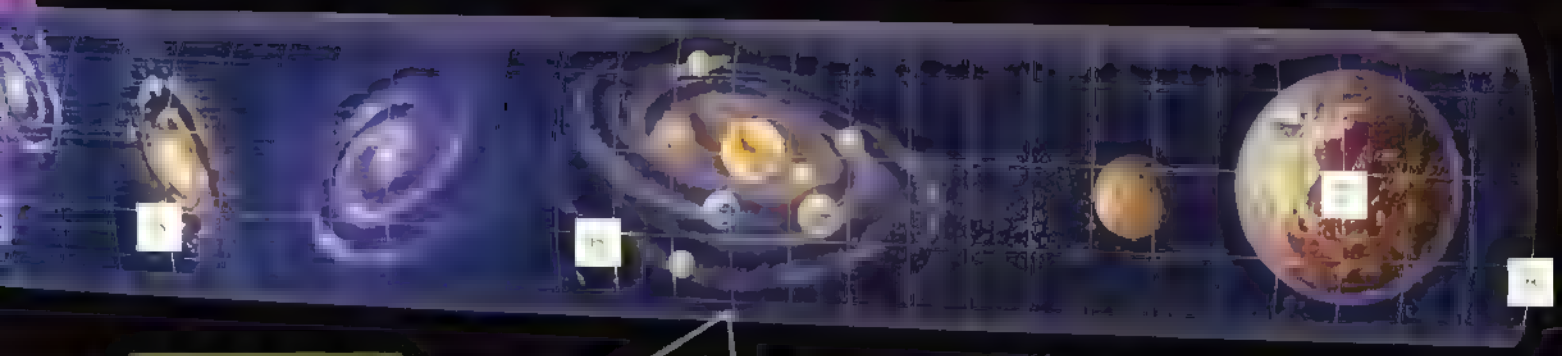
The attraction of this theory – called modular space-time – is that it might help solve another long-standing problem in theoretical physics regarding something called locality and a notorious phenomenon in quantum physics called entanglement. Physicists can set up a situation whereby they bring two particles together and link their quantum properties. They then separate them by a large distance and find they are still linked. Change the properties of one and the other will change instantly, as if information has travelled from one to the other

5 The universe accelerates

Having gradually slowed since the Big Bang, space-time begins to stretch at an accelerating pace due to something called dark energy.

7 The here and now

Today Earth is home to physicists who are pondering how best to combine quantum theory with Einstein's picture of space-time.



6 The Sun forms

Around 4.6 billion years ago a cloud of gas collapsed to form the Sun. Space-time is warped so much that planets soon form around it.

8 The Big Rip

As dark energy takes hold, the universe will eventually expand so much that even the space between atoms is stretched sufficiently to tear the universe apart.

1915

Einstein publishes the general theory of relativity

In a direct challenge to Newton's idea, Einstein says the force of gravity is a mirage. Instead it is caused by the curvature of the four-dimensional fabric of space-time.

1919

Eddington eclipse vindicates Einstein

Observations of a 1919 solar eclipse by English astronomer Arthur Eddington showed that the Sun bends light by the exact amount predicted by Einstein's general theory of relativity.

1974

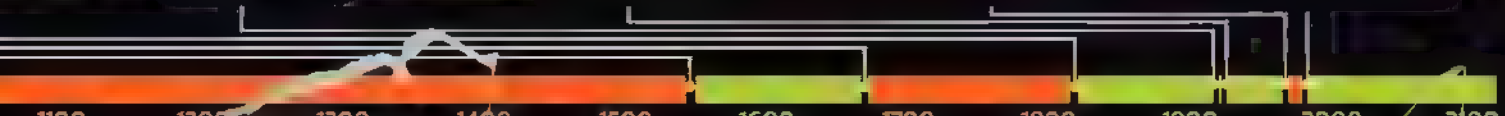
String theory arrives on the scene

Dalton's idea of indestructible atoms looks even more outdated as the electrons found inside atoms are proposed to themselves be made of tinier vibrating strings vibrating across multiple dimensions.

1988

Loop quantum gravity emerges

Physicists including Lee Smolin and Carlo Rovelli formulate the basic principles of LQG – a way of thinking space-time might be made of building blocks in the same way matter is constructed from atoms.



faster than the speed of light. Einstein was so perturbed by this phenomenon that he called it spooky action at a distance.

Modular space-time can accommodate such behaviour by redefining what it means to be separated. If space-time emerges from the quantum world, then being closer in a quantum sense is more fundamental than being close in a physical sense. "Different observers would have different notions of locality," says Minic, "it depends on the context." It's a bit like our relationships with other people. We can feel closer to a loved one far away than the stranger who lives down the street. You can have these non-local connections as long as they are fairly small," says Hossenfelder.

Freidel, Leigh and Minic have been working on their idea for the last eight years, and they believe they are slowly making progress. "We want to be conservative and take things step by step," says Minic, "but it is tantalising and exciting." It's certainly a novel approach, and one that looks to 'gravitationalise' the quantum world rather than quantising gravity as in LQG. Yet as with any scientific theory, it needs to be tested. At the moment the trio are working on how to fit time into their model.

"WHETHER IT DESCRIBES THE SPACE-TIME IN WHICH WE LIVE, WE DON'T REALLY KNOW UNTIL THERE IS AN EXPERIMENT"

This may all sound incredibly esoteric, but it could have a more profound effect on our everyday lives. "We sit in space, we travel through time, and if something changes in our understanding of space-time this will impact not only on our understanding of gravity, but of quantum theory in general," says Hossenfelder. "All our present devices only work because of quantum theory. If we understand the quantum structure of space-time better, that will have an impact on future technologies – maybe not in 50 or 100 years, but maybe in 200," she says.

The current monarch is getting long in the tooth, and a new pretender is long overdue, but which of the many options is most likely to succeed? When we decide, the resulting revolution could bear fruit not just for theoretical physics, but for all.

Above: One way to reconcile general relativity and quantum theory says reality is made of vibrating strings

REPLACING SPACE-TIME

String theory

Loop quantum gravity (LQG)

Modular space-time

Supergravity

Causal set theory

Space Science

Discover intergalactic theories and understand the science of space

126 Chaotic universe
Do we finally have a handle on [illegible] theory – and how it influences the world around us?

132 Our universe's missing link
Our model of the cosmos needs revision, but not without astronomers first assembling the pieces of a new cosmological puzzle

138 Interview: Didier Queloz & Michel Mayor
All About Space sits down with two of the three recent Nobel Prize laureates

"Kepler decided to go ahead because we demonstrated that there are plenty of other kinds of planets" Didier Queloz

CHAOTIC UNIVERSE

Do we finally have a handle on chaos theory - and how it influences the world around us?

Reported by Colin Stuart

When it comes to surviving in space, the tiniest things can be the difference between life and death. As Canadian astronaut Chris Hadfield said: "An astronaut who doesn't sweat the small stuff is a dead astronaut." That may be the case for human space travel, but astronomers are increasingly suspecting the same mantra also applies to the wider universe. When it comes to the cosmos, it seems chaos theory is king.

Chaos theory traces its origins way back to the 19th century. French polymath Henri Poincaré was attempting to win a prize of 2 500 crowns - a third of a professor's yearly salary - offered up by King Oscar II of Sweden and Norway to celebrate his 60th birthday. To win you had to predict the orbits of the planets. Isaac Newton's work on gravity allows you to foretell the future positions of two gravitationally intertwined objects with clockwork precision. Yet throw a third object into the mix and that ability vanishes. Poincaré failed to solve this three-body problem, but was awarded the prize nonetheless for important insights into why it is such a thorny conundrum to crack.

Russian mathematician Sofya Kovalevskaya also carried out important work on the problem. The puzzle is difficult because even the smallest changes in a system with many moving parts can lead to huge differences later down the line. That, in a nutshell, is the essence of chaos theory. "We wouldn't have chaos theory if we didn't study planetary orbits," says Dr Paul Sutter of the Flatiron Institute in New York.

American mathematician and meteorologist Edward Lorenz compared it to the flap of a seagull's wing affecting the weather. He later switched his metaphorical creature to a butterfly, and to this day it is still known as the 'butterfly effect'. In the 1960s Lorentz was using computers to try and predict weather patterns on Earth, but he found that the outcome was wildly different even though it looked as if he was modelling the same situation each time. Further investigation revealed that tiny rounding errors in the values fed into the computer blew up into major differences in the predicted forecast.

Today Lorenz gets the lion's share of the credit, but Mary Cartwright and John Littlewood analysed chaotic patterns in radio signals during World War Two. To this day chaos theory places a limit on how far into the future we can accurately predict the weather. Chaos theory makes meteorology an imperfect science.

Mathematicians have been studying chaos theory ever since Lorenz's insights. Somewhat counter-intuitively, they have found that chaotic systems are not as unpredictable as they first seem. "It helps us to identify patterns, key elements, hidden rhythms and orders in systems that are not normally apparent," says Sutter. Period doubling is just one example. In a chaotic system, the time it takes for a pattern of behaviour to repeat increasingly grows to twice as long as before. Eventually the behaviour takes so long to replicate itself that the system appears lacking in an underlying order - it looks

chaotic. However, there is method in the madness if you know where to look. In 1975 American mathematician Mitchell Feigenbaum, one of the pioneers of chaos theory, discovered that the ratio of the points at which the period doubles increasingly approach the number 4.6692... as the system becomes more chaotic. This number is now known as the Feigenbaum constant in his honour.

Applying chaos theory to the cosmos could help us to explain how the Earth came to be the life-hosting planet it is today. The Sun was one of many stars formed when a vast cloud of interstellar gas and dust collapsed around 5 billion years ago. "Tiny little changes in that gas cloud can lead to very big changes in the population of stars that form," says Sutter. An extra little clump of dust here, a tiny bit of extra spin there and the Sun could have been a very different star, or even not have formed at all. Star formation may look like a chaotic system,

© Hulton Deutsch / Getty

Above: French mathematician Henri Poincaré was one of the first to grapple with chaos theory

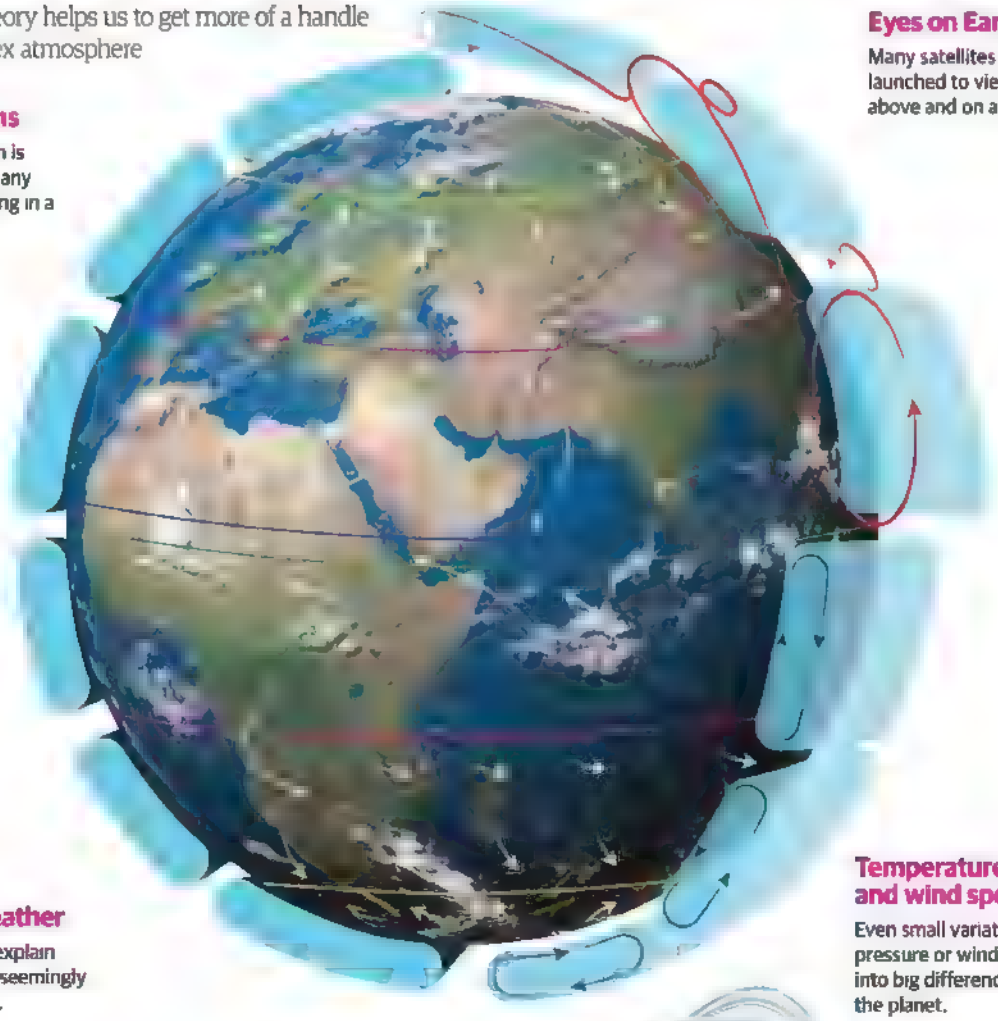
but there could be an underlying mathematical order that reveals the likelihood of forming the kind of stars suitable for sustaining habitable planets. In turn that could point us to the appropriate corners of the nearby universe to search for alien life. The creation of new stars is often studied by creating very complex computer simulations. "Chaos theory gives us a mathematical tool to help us get a handle on what's going on," says Sutter.

Why is our Solar System a good place for life to emerge, evolve and thrive? Our cosmic backyard looks serene today, with planets neatly drifting around the Sun in well-behaved orbits and relatively few unstable asteroids left to careen into them. Yet today's peace and quiet belies a tumultuous youth. "We suspect that a lot more planets formed around the Sun and some of them were on chaotic orbits," says Sutter. Tiny changes in their speed

> "It helps us to identify patterns, key elements, hidden rhythms and orders in systems" **Paul Sutter**

Applying chaos to the weather

The mind-bending theory helps us to get more of a handle on our planet's complex atmosphere



Our complex systems

The Earth's weather system is incredibly complex, with many different particles interacting in a variety of ways.

Eyes on Earth

Many satellites in orbit have been launched to view our weather from above and on a grander scale.

Jet streams

These fast-moving channels of air affect the weather in different parts of the world depending on their speed, latitude and movement.

Chaos solves the weather

Chaos theory attempts to explain underlying patterns in this seemingly random maelstrom of data.

Temperature, pressure and wind speed

Even small variations in temperature, pressure or wind speed can build up into big differences elsewhere on the planet.

Chaos theory in real life

It thrives across the universe – and also crops up in some everyday examples

Heart vs head

Parts of the human body may exhibit chaotic patterns. There's some evidence that arrhythmia – when your heart beats out of rhythm – may occur in a chaotic way. It's possible that our brain activity has chaotic tendencies, with some suggesting that electroencephalograms show it in action.

The natural world

Chaos is rife in the animal kingdom. Biologists studying the Canadian lynx have found that their population grows in a chaotic way. Small changes in food supplies, mating habits or the spread of diseases can become magnified into big differences in animal numbers.

Bless your cotton socks

In 1963, Polish mathematician Benoit Mandelbrot found recurring patterns in data on cotton prices from 1900 onwards that suggest they vary in line with chaos theory. They didn't follow the famous 'bell curve' as a lot of data sets tend to.

In a jam

Often traffic jams can seem to clear suddenly and without any obvious cause. Tiny changes to the flow of cars can build into sizeable log-jams that vanish almost as soon as they arrive.

Make codes harder to crack

Cryptographers – those responsible for setting and deciphering codes – are big users of chaos theory. A message is scrambled and unlocked using a series of keys, and some computer-based encryption methods – including online image encryption – utilise chaos maps to construct those keys.

Up to the job?

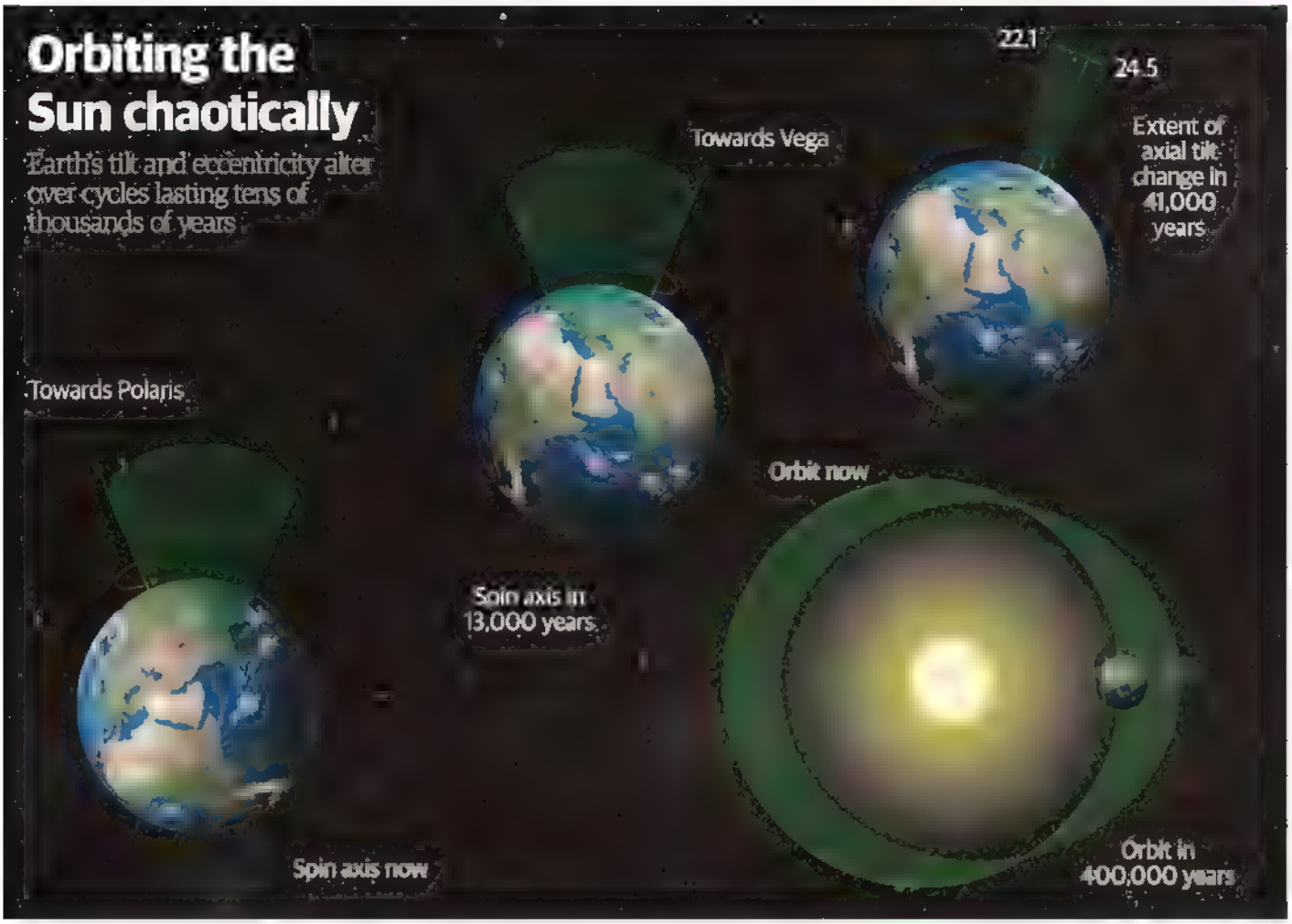
Even the labour market hasn't escaped the scrutiny of chaos theorists. The way we work, apply for jobs and move between companies could well follow chaotic patterns. Insights could lead to better decisions and a more streamlined workforce in the future.

Taking stock

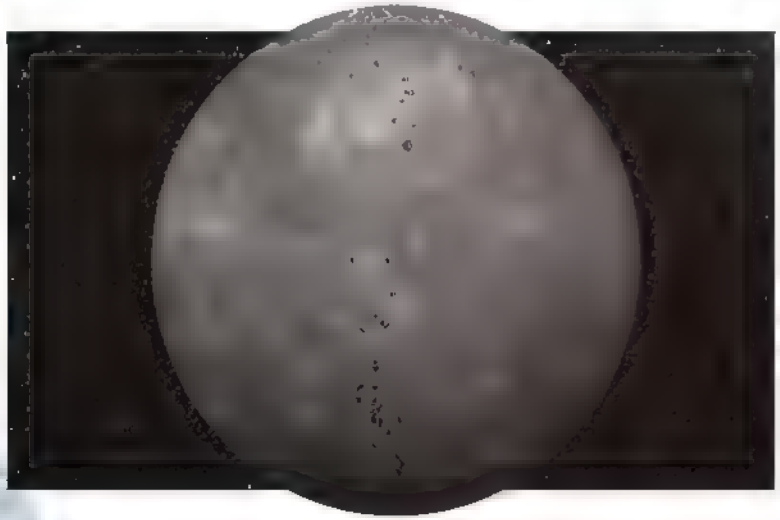
The ups and downs of the stock market are notoriously hard to predict. That's why the adage to success is "time in the market rather than timing the market". It may be possible that chaos theory could reveal hidden patterns in the lightning-fast trades on the world's exchanges.

Better understanding babies

The chaos in our lives starts early. Researchers have shown that they can better understand the warning signs of a condition called fetal hypoxia – where a developing fetus is starved of oxygen – if they model the situation using chaos theory.



and positions would have been amplified into considerable effects. Eventually they either crashed into other planets - just such an event is thought to have formed the Moon - or were jacked up onto such steep orbits that they were ejected from the Solar System entirely. "Only the ones born in good places at good times get to stick around," Sutter summarises. Working out what constitutes a good place or good time is key in hunting out habitable worlds in other solar systems. Astronomers have spotted a whole host of weird-looking solar systems, including a planet that orbits its star in the opposite direction to its neighbours, probably because its orbit became so inclined that it flipped right over the poles of the star. This work is a shot in the arm for subscribers to the Rare Earth hypothesis - the notion that so many factors have to be just right for life that living planets like our own are few and very far between.



Below: As the smallest planet, Mercury is most susceptible to the effects of chaotic changes

Yet even the chaos in our Solar System is still not complete. Over a human lifetime the path of the planets is predictable, but tiny interactions between worlds can build up to sizeable changes in the future. Just as the weather forecast begins to break down over timescales of more than a week, we can only predict the orbits of the planets for the next 40 million years or so - an astronomical heartbeat compared to the 4.6 billion years it has been around so far. It wouldn't take much to upset the whole system, and one planet is particularly susceptible to the ensuing melee. "There's a chance that Mercury could be ejected entirely," says Sutter. The orbit of the Solar System's smallest planet is constantly shifting around. The point at which it reaches its closest approach to the Sun - its perihelion - moves by 15 degrees every millennium. Jupiter's perihelion is moving too, and if the two ever get into the same rhythm then that could spell the end of Mercury. There's a one to two per cent chance its orbit will be seriously disrupted in the next few billion years. It could be ejected from the Solar System, or worse

"Chaos theory gives us a mathematical tool to help us get a handle on what's going on" **Paul Sutter**

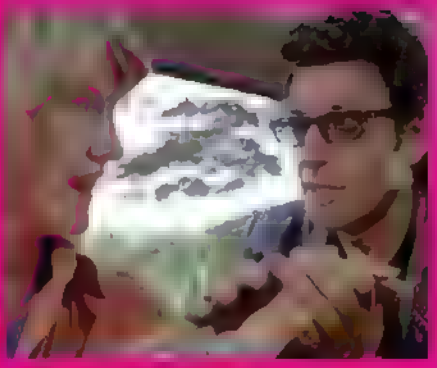
it could smash into the Earth. An inner Solar System without its first planet would itself become unstable. That could lead to Mars and Earth nudged into a calamitous collision. It just shows how much chaos theory matters.

We already have some evidence that the astronomical furniture can be significantly rearranged. Nearly a decade ago, astronomers spotted the first 'rogue' planets – worlds jettisoned from their home systems to wander the emptiness of space alone. There could be one Jupiter-sized orphan for every four stars in a galaxy like our Milky Way. Five per cent of Earth-sized planets would be able to cling onto any moons as they exited their system. Ejected planets form a big part of our best model of the formation of our Solar System. Astronomers running computer simulations discovered that you end up with a solar system that looks more like ours if you start with five giant planets instead of four. Except we don't have a fifth giant planet now. Either it went rogue or it is still languishing in the backwaters of the Solar System. That's because astronomers increasingly suspect there is a ninth planet marooned far beyond Neptune. This 'Planet Nine' could well be a failed rogue planet that was unable to exit the Sun's gravitational clutches entirely.

Even if the chaotic Solar System doesn't set us on a collision course with our neighbours, it could still have telling consequences for our climate. In 2017 researchers studying layers of rock in the Niobrara Formation in Colorado found a key piece of evidence that Earth and Mars interacted in an unusual way nearly 90 million years ago. At the time there was a sea running through the middle of North America, and sediments falling

Below: Star forming regions – such as the Eagle Nebula – could be governed by chaos theory

©NASA/ESA



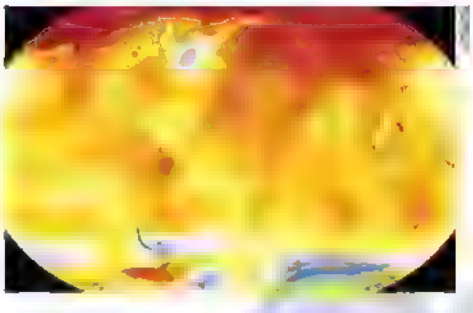
Why is chaos theory important?

to the sea floor were compressed into the rock seen there today. A team led by Professor Stephen Meyers of the University of Wisconsin-Madison found a difference in the clay levels between the layers of rock laid down over millions of years. A warmer, wetter climate leads to more clay being flushed into the sea from rivers than when the weather is drier. Alternating layers indicating wet and then dry climates were stacked up in a such a repetitive fashion that Meyer concluded there must be some cyclical phenomenon driving the changes. He points the finger at Mars and its ability to change the eccentricity of Earth's orbit. Eccentricity is a measure of how much a planet's orbit deviates from a circle. Any changes to this key value would change how much warmth the Earth receives from the Sun and provoke the knock-on climatic effects that come with that. It would also make our seasons unequal as the Earth would spend more of the year in one part of its orbit than another.

The Earth can be affected in other ways, too. The tilt of our axis can vary under the gravitational influence of the other planets. Right now we lean at 23.4 degrees from vertical, but that varies between 22.1 degrees and 24.5 degrees over a 41,000-year cycle. This also changes the amount of sunlight we receive, particularly in summer and winter when we are leaning towards and away from the Sun. If small changes build up in a chaotic way, this cycle may get out of rhythm. Equally, the Earth's axis moves around as our planet is wrenched by the Sun and Moon, tracing out a circle every 26,000 years or so. In the 1920s Serbian scientist Milutin Milankovitch combined all these effects and their regular effect on the Earth's climate, suggesting we go through periodic changes called Milankovitch cycles. They too may be susceptible to chaos.

> "We suspect that a lot more planets formed around the Sun – some on chaotic orbits" **Paul Sutter**

As we move into a future where human-made climate change is going to bite harder and harder, it has never been more important to understand the full range of factors that can influence the way our atmosphere receives, stores and transports energy. A better understanding of chaos theory goes hand in hand with more accurate climate models and a better picture of how tiny changes in the layout of the Solar System can translate into big effects on our already-warming planet.



Top: The Moon formed when a chaotically disrupted planet smashed into Earth

Above: A better understanding of chaos allows us to accurately predict climate

OUR UNIVERSE'S MISSING LINK

Our model of the cosmos n[illegible] revision, but not without astronomers fir[illegible]ssembling the pieces of a new cosmological puzzle

Reported by Lee Cavendish

Observation and theory make up the two pillars of scientific research. Without observations, there is just a theory with no substance, and without theory there is just a series of measurements with nothing to extrapolate from them. But what happens when one does not satisfy the other? Recent research about the expansion of the universe and the model that astronomers use to predict its history has caused tension between these two pillars. It appears as though recent measurements of galactic distances over a hundred million light years away and their respective recession speeds have contributed to a persistent discrepancy that keeps cropping up.

Measuring the distance to galaxies has been a relentless objective of astronomers since the beginning of the 20th century. Although many names can be attached to discovering the expansion of the universe - such as Vesto Slipher, Carl Wirtz, Knut Lundmark and Georges Lemaître - it was the work of an American astronomer called Edwin Hubble, the eponym of a law, a constant and a space telescope, who had the most profound effect on this area of research.

In the 1920s Hubble used a telescope at the Mount Wilson Observatory, California, to study the cosmos in unrivalled precision. By doing this he discovered that what astronomers thought were nebulae - clouds of gas and dust illuminated by internal stars - were actually other galaxies outside the Milky Way. He then went on to measure the distances to these galaxies by studying their internal Cepheid variable stars and inferring the distances using a luminosity-distance relationship.

Cepheids were first cited as distance markers in 1912 by another American astronomer, Henrietta Swan Leavitt, who noted that the regular luminosity fluctuation of variable stars can be mathematically manipulated to derive the distance between Earth and that star. This is one class of astrophysical object used to measure distances, commonly referred to as 'standard candles'. By studying Cepheids in distant galaxies and using measurements gathered by other astronomers, Hubble was able to obtain distance measurements for 46 galaxies and uncover something truly groundbreaking.

In 1929 Hubble announced that there is a proportional relationship between a galaxy's distance from Earth and its recession velocity. In other words, the greater the distance between Earth and the galaxy, the greater the speed at which the two are moving apart. This is now known as 'Hubble's law' and the accompanying constant of proportionality - known as the Hubble constant (H_0) - was predicted to be 500 kilometres (310 miles) per second (the speed) per megaparsec (distance in units favoured by astronomers). However, this was not correct at all, and actually implied that

Right: Standard candles are shining examples of astrophysical objects used to calculate cosmic distances

Below: The Hubble Space Telescope has been just as influential to astronomy and cosmology as its namesake

HOW DO WE CALCULATE THE HUBBLE CONSTANT?

The problem causing the discrepancy could lie somewhere in these methods

1 Parallax

Parallax is an ancient method for measuring the distance to relatively nearby stars up to approximately 65 light years away using Earth-based measurements – or 326 light years if having used the ESA's Hipparcos mission. This method uses trigonometry to measure the displacement of a star's background, having observed it from the opposite side of the Sun. This method is commonly used as the first step on the 'cosmic distance ladder' which astronomers use to calibrate other results.

2 Cepheids

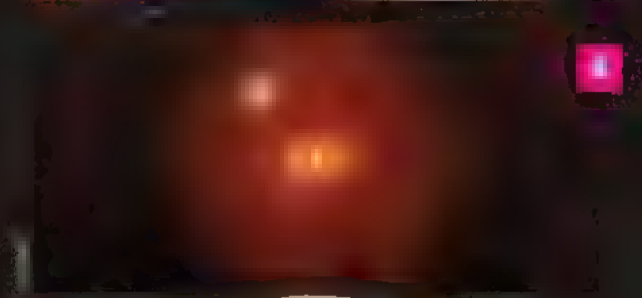
Cepheids are unstable stars that are coming to the end of their lives. During this period of imbalance, there is a periodic pulsation to the star. From Earth this pulsation appears as a timely dimming and brightening. Astronomy changed when Henrietta Swan Leavitt discovered the periodic pulsating could mathematically infer the star's distance up to 20 million light years using what is now known as the 'period-luminosity relationship'.

3 Type Ia supernovae

Another standard candle that helped provide a more recent Hubble constant figure are Type Ia supernovae. These are not stars by definition, but are instead the explosive events that mark the end of a white dwarf star. Specifically one more than 1.44 times the mass of our Sun. The peak luminosity when they explode is consistent across the universe, and therefore astronomers can take the observed magnitude and use a similar distance-luminosity relationship equation to determine the distance to galaxies tens of millions of light years away.

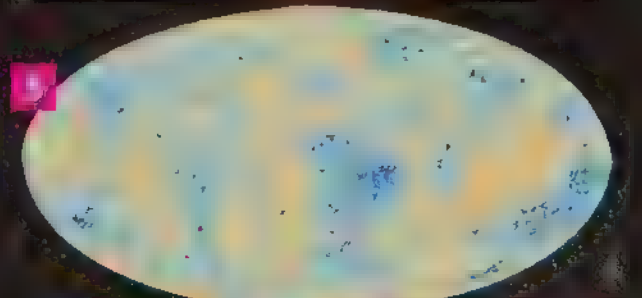
4 Redshift

This is the ultimate ruler when it comes to working out cosmic distances. In the past galactic redshifting revealed the distance to the farthest known galaxy from Earth, GN-z11, which is 13.4 billion light years away. This method requires spectroscopic data of a galaxy, then astronomers determine how far the emission or absorption lines for elements have shifted to the red end of the electromagnetic spectrum.



5 Cosmic microwave background

The CMB is leftover heat radiation from the Big Bang that can only be seen when observing the universe through microwave wavelengths. This provides visible and accessible information about what the universe was like over 13 billion years ago. In order to paint the best picture, astronomers have produced cosmological models that fit the CMB data. It just so happens that these models predict a different figure for H_0 than what is calculated using standard candles and megamaser geometry.



6 Megamaser geometry

Masers are radio analogues for visible-light lasers, and can therefore be easily picked up by Earth-based observatories. By measuring a maser's centripetal acceleration and radial velocity, the Megamaser Cosmology Project then applies geometry to calculate the distance between Earth and the host galaxy. This is unique because it is independent of standard candles and the CMB, and therefore the results carry more weight and provide a new outlook on the discrepancy.

THE TELESCOPES THAT YIELDED THESE RESULTS

the universe was only 2 billion years old. At the same time geological records showed Earth was at least 3 billion years old, which certainly had people scratching their heads

Over the years techniques have been refined, and other standard candles have been added to the astrophysical roster in order to come to a more believable figure. In 2019 Dr Adam Riess of the Space Telescope Science Institute (STScI), Johns Hopkins University in Baltimore and Nobel laureate of 2011 arrived at a figure of 74.03 kilometres (46 miles) per second per megaparsec using Cepheid stars, type Ia supernovae and the Hubble Space Telescope. This is the figure that will be commonly quoted when referring to the Hubble constant. This is arguably the most influential constant used within astrophysics and cosmology. It is based on undeniable evidence that the entire universe is expanding at an increasing rate at larger distances, with Earth being no geocentric exception to the rule. The universe is homogeneous and the Milky Way is travelling through the cosmos just like everything else

The Hubble constant also means that there is a timeline to the universe. The cosmos must have originated from a single point of initial expansion, evolved over the last 13.8 billion years and will perhaps come to a crunching, freezing or ripping

"DARK ENERGY PERMEATES ALL OF SPACE AND CREATES A TENSION IN THE UNIVERSE THAT CAUSES THE EXPANSION OF THE UNIVERSE TO ACCELERATE" JIM BRAATZ

end at some point. The discovery of Hubble's law and its constant had major implications for the Big Bang theory, dark energy and the current standard model of cosmology Lambda Cold Dark Matter (LCDM) theory

"[This theory] describes a universe that is governed by Einstein's theory of gravity and general relativity 'The model says that the universe is made mostly of 'dark energy' and 'dark matter', neither of which we understand very well," explains Dr Jim Braatz, an astronomer at the US' National Radio Astronomy Observatory (NRAO) and lead of the Megamaser Cosmology Project, to **All About Space**. "Dark energy permeates all of space and creates a tension in the universe that causes the expansion of the universe to accelerate as it ages. Dark matter is a component of the universe that exerts gravity but does not shine in any sort of light. This type of matter - called baryonic - which makes up all the stars, gas, dust, planets and people, is a very small part of the universe according to this model, and most competing models too."

It has been no easy ride confining the number for H_0, and the figure has changed continuously over the years as astronomers attempt to measure cosmic distances and recession speeds using different methods. The scientific community needs to unanimously agree upon a figure, and that can only be done by arriving at the same figure - or having overlapping uncertainty percentages - using unrelated and unique techniques. This makes it hard to argue against the undeniable evidence, and is essentially the scientific process for anything. In this particular case the Hubble constant has also been inferred using data collected from relic radiation left over from the birth of the universe, which is known as the cosmic microwave background (CMB).

Scientists have developed models of the universe to fit the observations and measurements taken from the CMB by the European Space Agency's (ESA) Planck satellite The figure they arrived at was 67.4 kilometres (41.9 miles) per second per megaparsec, with an uncertainty of less than a per cent. That the uncertainty bar doesn't overlap with the uncertainty bars derived from astrophysical techniques has since created a discrepancy

The Megamaser Cosmology Project is an international effort to measure the Hubble constant using precise geometric distances. This outstanding team effort has derived a figure for the Hubble constant without using any standard candles or the CMB, but instead using radio telescopes in the US

Above: Theoretically a dark matter web permeates throughout the entire universe

Below: A single galaxy can potentially contain millions of supernovae, Cepheids, megamasers and other cosmic lighthouse signals used to calculate distances

© Yale University - OPAC

WHAT ARE THE POSSIBLE EXPLANATIONS?

Dark energy's early influence

Dark energy, which makes up about 70 per cent of our universe, could have provided an unexpected input of energy after the Big Bang which caused the universe to expand faster than predicted. This is called the 'early dark energy' theory.

A new subatomic particle

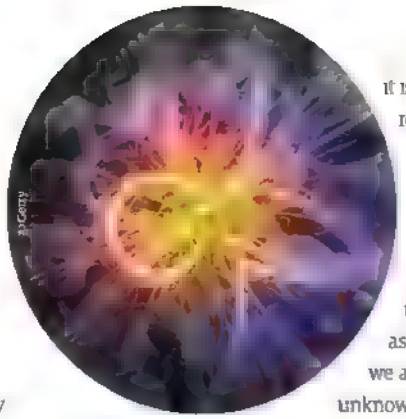
This could provide a new objective for the next generation of particle accelerators. The discrepancy could be explained by the existence of a subatomic particle that moves close to the speed of light, which when influencing the universe collectively is also referred to as 'dark radiation'.

Stronger dark matter interaction

Dark matter, which makes up approximately 25 per cent of our universe, could interact with ordinary matter, which makes up just five per cent, with more intensity than originally thought. The issue is that dark matter cannot be observed directly. It emits no light and only interacts with ordinary matter through the medium of gravity.

Waiting for a new theory

This is a complete mystery, and while astronomers stay determined to provide a figure for the Hubble constant with as little uncertainty as possible – the aim being less than one per cent - the same people could be coming up with new and groundbreaking theories that could bind the two observations.



and Germany to identify water-bearing molecules in galactic centres.

"The centres of most galaxies have supermassive black holes. If there is sufficient dust and gas near these black holes, the material can form an accretion disc that feeds material to the black hole and it can radiate profusely. Water vapour is a trace constituent of the accretion disc, and fortunately it can emit maser light at radio wavelengths. Maser, like 'laser', is an acronym. It stands for microwave amplification by stimulated emission of radiation," explains Dr Mark Reid, a senior radio astronomer at the Smithsonian Astrophysical Observatory, Massachusetts, to **All About Space**. "We see bright clumps of maser emissions from the water vapour and can measure Doppler shifts, positions and angular motions. Simplifying things a lot, if you measure a galaxy's speed and angular speed, you can get a distance.

"The technique used to measure the extremely small angular motions of the masers is called very-long-baseline interferometry (VLBI). This technique requires making measurements on a large number of baselines in order to reconstruct an image of what the radio sky would look like were we to have a telescope the size of Earth and could see radio waves," Reid continues.

In total the distances for six galaxies - UGC 3789, NGC 6264, NGC 6323, NGC 5765b, CGCG 074-064 and NGC 4258 - were measured, ranging between 168 million and 431 million light years from Earth. This research gave a figure of 73.9 kilometres (45.9 miles) per second per megaparsec as the Hubble constant, with an uncertainty of plus/minus three kilometres (1.86 miles) per second per megaparsec. This figure is therefore more consistent with the standard candle method.

"It is really essential that we get small uncertainties and unbiased measurements. Geometric methods can be particularly valuable because those methods and their uncertainties are entirely unrelated to those associated with standard candles," says Braatz. "Moreover, a distance measurement at large distances beyond about 150 million light years provides a direct measurement of H_0 in one step, rather than using the traditionally staged calibrations known as the 'distance ladder'.

"Our measurement of the Hubble constant is very close to other recent measurements, and is statistically very different from the predictions based on the CMB and the standard cosmological model. All indications are that the standard model needs revision."

So what does this mean for the standard model? "There is something in fundamental physics that is missing from the model, and we don't know what it is," says Braatz. "It may be related to our understanding of particle physics. For example, if some new type of particle played an important role in the growth history of the universe, it could show up as the type of discrepancy we are seeing. It may be an unknown and mysterious manner of interaction between different types of matter. It may be an exotic new form of energy."

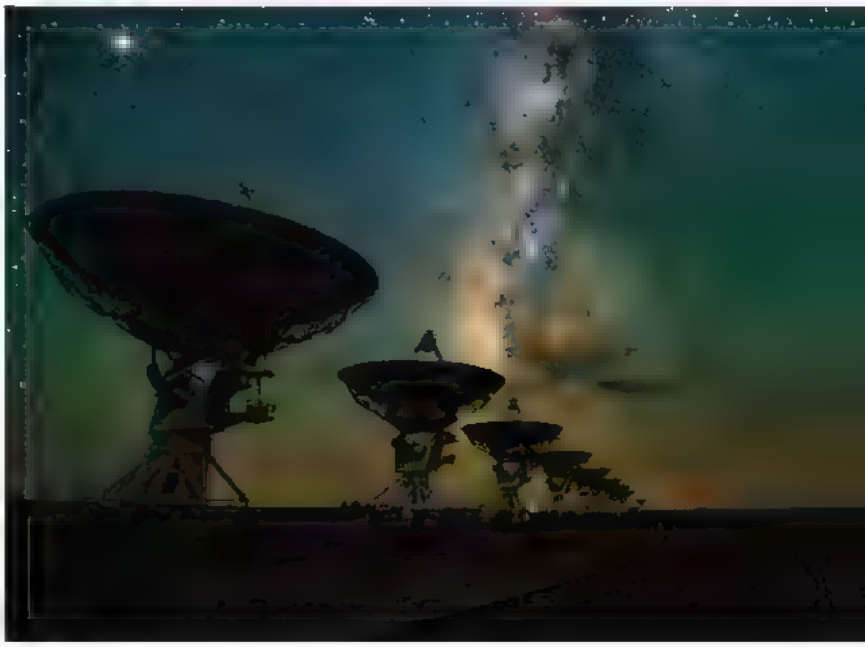
"If real - and not just some subtle measurement issue - the H_0 discrepancy looks to be a fundamental clue to new physics," Reid explains. "It could be that the very early universe does not follow the favoured model, the LCDM theory, or that there is an extra type of neutrino or some other very basic lack of knowledge."

There are a number of possible reasons as to why this discrepancy is evident, and it is possible that there is a mysterious force at play that physicists are completely blind to. This would mean changing the standard model - which in the past a large number of astronomers believed was the solution to cosmology's greatest mysteries - to suit the observations. At the same time teams of astronomers are still improving their analysis techniques in order to improve their uncertainty.

But as the technological and engineering age advances, this means new telescopes and technologies are being taken advantage of for scientific benefit. For example, when Riess won his Nobel Prize in physics in 2011 along with Saul Perlmutter and Brian Schmidt, they had the help of recently introduced CCD imaging sensors. For the megamaser geometric method, Braatz believes that the Next Generation Very Large Array (ngVLA), a radio telescope array that could be up and running as early as 2028, could provide the improved sensitivity required to reduce the uncertainty when measuring the Hubble constant.

Whatever the eventual outcome, it is clear that there is a call for attention towards what can only be referred to as a cosmic conundrum. There needs to be more observations, less uncertainty and a theory that can account for this discrepancy in figures between astrophysical and CMB measurements. Could this mean trying to find a new particle? Could this mean re-evaluating our understanding of dark matter and dark energy? Or was there an unaccounted event in the universe's early evolution that could explain this?

"IT IS REALLY ESSENTIAL THAT WE GET SMALL UNCERTAINTIES AND UNBIASED MEASUREMENTS. GEOMETRIC METHODS CAN BE PARTICULARLY VALUABLE" JIM BRAATZ



Above: A new particle may need to come to light in order to explain this discrepancy

Right: VLBI utilises worldwide radio antennae which collaborate and form an Earth-sized radio telescope - albeit a very patchy one

INTERVIEW BIO

Professor Didier Queloz
Didier Queloz discovered 51 Pegasi b as a PhD student at the University of Geneva, Switzerland. Now he is a professor at the Cavendish Laboratory at the University of Cambridge. He also won the Wolf Prize in Physics in 2017.

Professor Michel Mayor
Michel Mayor is professor emeritus at the University of Geneva's Department of Astronomy. He has been at the University of Geneva and the Observatory of Geneva since 1971 in several positions. He retired from his position as professor in 2007.

Above: An artist's impression of 51 Pegasi b and its host star, which is 50 light years away from Earth.

DIDIER QUELOZ & MICHEL MAYOR

WINNERS OF THE NOBEL PRIZE IN PHYSICS 2019

All About Space sits down with two of the three recent Nobel Prize laureates to talk about what it was like to win the prestigious award, how their discovery has had profound ripples in the exciting field of exoplanet research and why this is only the start...

Reported by Lee Cavendish

Right: An illustration of Queloz and Mayor, two of the winners of this year's prestigious award

First of all, congratulations on winning the 2019 Nobel Prize in Physics. For those who don't know the story already, could you please give us a brief recap of the discovery of 51 Pegasi b? What were your intentions going into the research? How did you feel when you made the discovery?

MM: Yes, it [exoplanet research] was a very hot topic in the last part of the 21st century, but few people were really working on it. It was only a very small number of people working on the domain at the time. Nevertheless, we started with our French colleague from Marseille and Haute Provence Observatory. We started building a new kind of spectrograph with a much higher sensitivity precision and so on.

We started at the end of the 1980s, and in 1993 or 1994 it was ready to measure. And we asked for observing time, because it was not automatic. We got about one week every two months to measure solar-type star selection - 142 stars - and we were very surprised that we got the first hint of an exoplanet at the end of 1994. This was actually a big surprise, because the theory at the time for the formation of giant planets - like Jupiter and so on - was its period should be larger than ten years. It was not a small discrepancy because 51 Peg's orbit is only four days. It was a discrepancy by a factor of a thousand.

I decided to postpone the announcement for the next season. In July 1995, with Didier, we started to remeasure the same star to check if the period was present with exactly the same period, with the same amplitude and the same traits. This was a check to eliminate any uncertainty.

We then decided to publish the paper in *Nature* at the end of August, and then there is the review procedure. It was potentially a hot topic, and so *Nature* asked for not only two referees, but three.

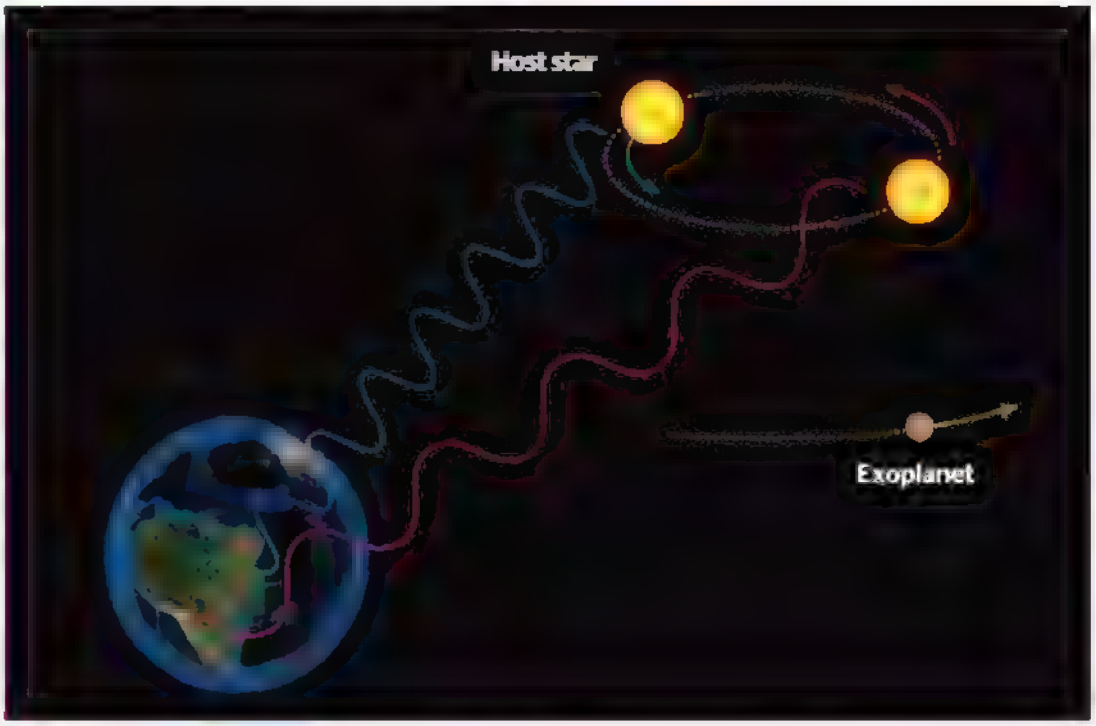
In the meantime, I was going to announce the discovery at a meeting in Florence, Italy. It was a huge, very important meeting with something like 300 colleagues, all interested in solar mass stars. It was a good place to discuss this, but I asked if anybody had some comments, because I was still slightly anxious that the interpretation was not a good one. I received a message from HR saying, "No. We are not allowed to speak [about the discovery] because of the embargo policy of *Nature*."

We already had a lot of journalists and Italian television crews there because the rumours were spreading around. This was the start of this huge media interest.

DQ: At that time there were no exoplanets, so the main difficulty that we had to deal with was first to convince ourselves that indeed it was a planet. This is because it didn't fit, at all, the picture that you would expect for finding another Jupiter. Most of the article was about dealing with that and making sure that this was real. And then it was to make sure we had comprehensive evidence that it could not be something else.

When we could reach the final decision that it must be a planet, either way we came up with this amazing situation that was almost apologising when we announced the object. [We said that] we

The story behind the discovery



ESO

"It was kind of a rough time I must say, because we were really facing huge scepticism for some time" **Didier Queloz**

Above: The radial velocity method of exoplanet detection was used to discover 51 Pegasi b

Right: Queloz provided the Nobel Prize Museum with the key that was used to enter the Haute-Provence Observatory during their studies

Far right: Probing atmospheres is key to finding an Earth-like exoplanet

can't find any other explanation but [the 51 Peg signal] being a planet, while being aware that the planet is weird, because it's a hot Jupiter - it doesn't exist in theory. It wasn't predicted at all

That was mostly the mood at the time, and you can imagine the community reacted to that with a lot of scepticism because it was the first exoplanet which was something that people were used to having been announced in the past and proven wrong. It was kind of a rough time I must say because we were really facing huge scepticism for some time

What were you doing when you found out you had won the Nobel Prize?

MM: When I received the announcement in fact I was not receiving any telephone calls before It was by chance I connected myself [to the internet] just before leaving San Sebastián to the airport. I connected myself to the site of the Nobel, and it was at a good moment when they did the announcement in Stockholm, and the first sentence I heard was, "This year it will be devoted to people having contributed to the knowledge of the cosmos."

It was great. And then after a few minutes I was obliged to leave to go to the airport, so it was a little bit stressful. I was then contacted at the bus station to have a short interview with the Nobel Foundation, but it was awfully noisy, so it was completely impossible. I asked them to do a second call when I will be waiting for the plane at San Sebastián airport. It was okay. It was really nice, but a bit stressful

DQ: Well, I was absolutely caught by surprise, because I was in the middle of a meeting. I didn't even realise that was the day of the announcement, and finally I got a phone call from the university from the PR office. After the announcement they were telling me, "Are you aware that you just won the Nobel Prize?"

I couldn't believe it. It took me some time to realise, and then I got 20 peaceful minutes. This was because I was with a team which was a scientific meeting for another project, and after the PR team came up and took care of me, I got dragged down to London and was in front of a crew of journalists. There were so many people and so many cameras. It was quite an amazing time. It did not seem very real, actually. [Laughs]

How does it feel to be in the same bracket as physicists such as Albert Einstein, Niels Bohr, Richard Feynman and so on?

MM: It is very impressive because in some sense, we cannot compare ourselves to these people. But I realised suddenly that what we did had a very huge impact for the field. It's probably the reason why we have been chosen for this huge prize

DQ: We received a lot of messages from friends and colleagues working in the same field, and everybody is really super excited because it is acknowledging 24 years of work on a new field. When you look back, what has happened in the last 24 years, it's just amazing. There are so many people and results from this field. And now we are finding out the atmospheres of planets. I mean, we are measuring the wind on some of them.

I think it's reflecting not only the impact of the first discovery, it's also reflecting the huge impact of a community working in this field, and you feel this complete shift in the paradigm of where we sit in terms of solar systems - especially when we compare ourselves to other systems in the universe. In a way we have been very useful, which is good. I'm very pleased that the community is thrilled.

Do you think this is the first Nobel Prize win of what could be many for exoplanetary research?

DQ: Yeah, I really believe so, because, again, this is a new field. We've just kick-started it. I mean, you have to imagine right now that there are thousands of people working in this field, and I really hope that having this one acknowledging the field, there will be way more awards. Not only the Nobel Prize, but other awards for other pieces of work. And you can just think ahead a little bit and ask yourself, 'What about when are we going to find some evidence for life?' I mean that would obviously be another Nobel Prize. You can imagine that between that kind of discovery and the first one, there may be some other aspect that has had a huge impact on the field.

In a way, I'm glad that now the field is clearly acknowledged by physicists as a main field of astrophysics, because this is a reality. We have to now recognise the fact that there is a new field of extremely active research that attracts a lot of students right now, with so much to find and so many big surprises to unravel.

There are plenty of upcoming missions to be very excited about. NASA launched the TESS mission just last year. The European Space Agency is going to launch the CHEOPS satellite soon and there's also going to be the James Webb Space Telescope in 2021. How close do you think we are to finding Earth 2.0?

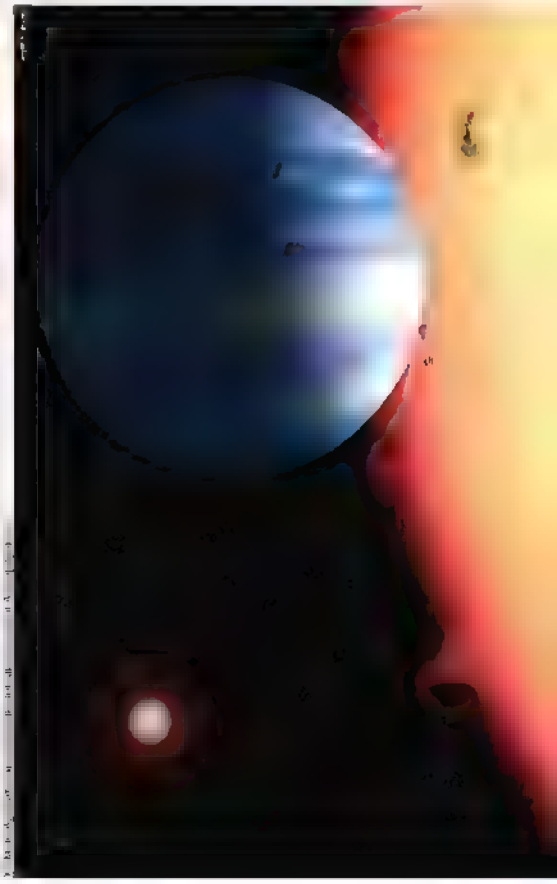
MM: I will mention first the CHEOPS mission. It's a mission like TESS, but with a slightly different focus, and then after you will have, for example, [the ESA's] PLATO mission. This will be a very ambitious mission that will be launched in 2026. You have plenty of missions to be developing for the future, and already today, as you mentioned, TESS is publishing a lot of interesting topics, and we are quite interested in this mission. This is because TESS provides the size of an exoplanet, but you don't have the mass. What we are doing is to do Doppler measurements to get the mass. If you have the mass and the size, you can start to see based on its density - if it is a rocky exoplanet or a gaseous exoplanet. Determining the physical state of a planet is a completely new field, due to the combination of these two techniques.

DQ: Well first, I'm not very comfortable with the concept of Earth 2.0, because it implies a lot of stuff. I mean, we really specify here something that would be like the Earth, which means not only talking about a planet that would have one Earth mass and one Earth radius, you're also talking about a planet that has similar plate tectonics, a similar atmosphere and similar evolution. We are very far away from doing that right now because we don't have the equipment to be able to say that an exoplanet is really like the Earth.

But the key message is, we're working on it. There are a lot of ongoing programmes that are probing the question of 'what is a 'rocky planet?' We're learning, because there are many kinds of rocky planets, as mentioned by Michel, that we are finding with TESS.

Now, the next stage is we have what I call 'Earth like', which is that they look like the Earth. In that sense, Venus looks like the Earth as well. It's about the same kind of orbit, it's got the same kind of mass and the same kind of size.

And then there will be some space missions that are going to get something about the atmosphere on some of the systems that look a bit like the Earth, like the TRAPPIST-1 system, for example. This is something that's going to happen in the next ten years mostly, thanks to the James Webb Space



Telescope, or other ground-based telescopes such as the Extremely Large Telescope of the ESO.

MM: Presently the instrumentation to detect the precise velocities with new instrumentation is extremely precise. This is not the difficulty. Presently one of the most important difficulties is the magnetic activity of our star. When you say you are measuring the velocity of a star, and to detect the small wobble due to the planet, you have to take a mean [measurement] of all the velocity of atomic spaces in front of us. If you have magnetic activity, we're not objective. This is really a limitation to detect very small planets like the Earth. You have to remember that the wobble induced by the Earth on the Sun is only something like eight centimetres per second. It's so small and the stars are not really helping us.

William Borucki, the principal investigator of the Kepler mission, had a lot of adversity in trying to get the mission started and had a lot of setbacks. Did you have any similar sort of adversity in your research of exoplanets, or was it not taken seriously enough by people?

DQ: I'm not sure that's the reason why he had difficulty. I mean, the concept of not being taken seriously. I think the idea of looking for planets around other stars was serious business at the time. The problem was not the question, it was whether there was some hope to detect anything. I think the problem that Bill Borucki had at that time was to demonstrate that statistically it would be meaningful to do this programme for two reasons.

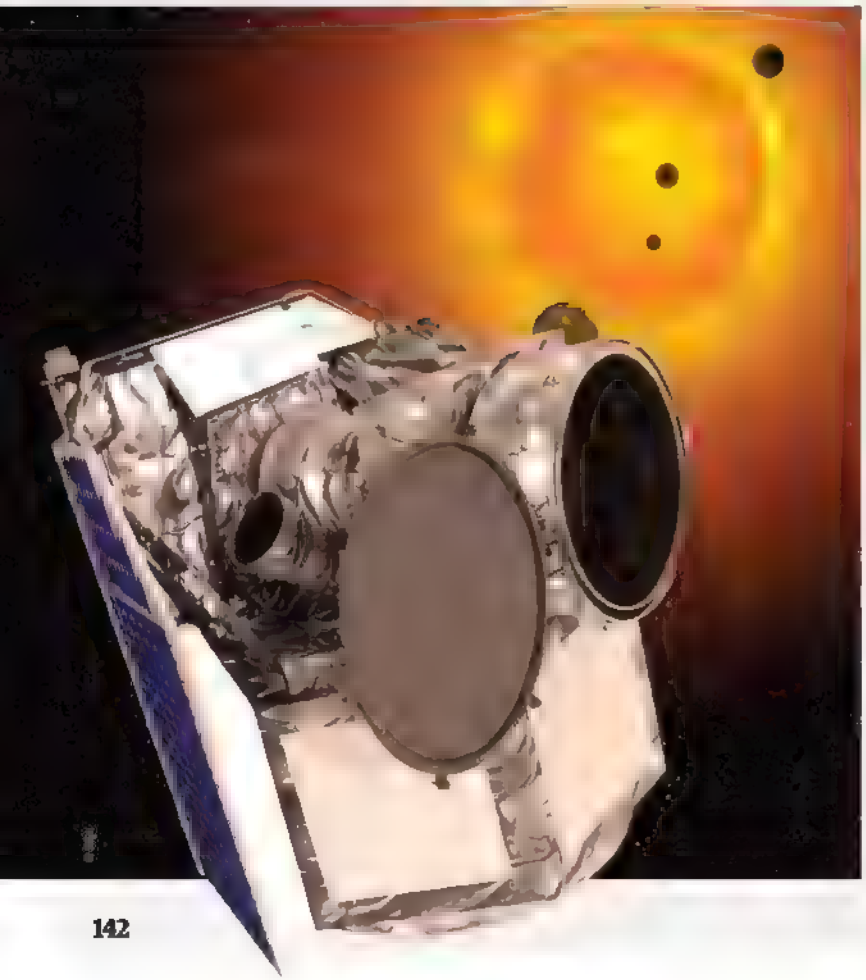
First, I mean, nobody had carried out the performance that they had in mind. You need to talk what we call ten parts-per-million accuracy, which is something that nobody had achieved before. And I think he had to do quite a lot of benchmarking to demonstrate that just a detector could reach this. The other problem they had, and in a way we helped him on that aspect, is if you don't have a mass, then you realise that finding an Earth is very statistically difficult. This is because it's very rare to get the transit. And actually if you really think about it, detecting an Earth, the Kepler mission has entirely failed on this, because they have not found any. The reason why Kepler decided to go ahead is because we demonstrated that there are plenty of other kinds of planets.

I think that's kind of the paradox of the field. I think the field was helped by the paradox of the fact that there are actually in the entire universe, plenty of other kinds of planets that are very easy to pick up by the transit. If you count today how many planets are known around other stars, most of these detections have been found by their transit, because they are short period planets.

That's an interesting aspect of it, to realise that the Kepler mission was granted the 'go ahead' very shortly after the first transiting planet was found. I think Borucki got the mission to go ahead because some people suspected that there will be all these kinds of planets as well, and the mission will detect them.

Sometimes science goes in a strange way, and there's something that I learned recently. It is something that a lot of people mentioned, some other Nobel Prize winners, which is the gambling aspect of a successful discovery. You know, in a way Bill Borucki is a gambler, because he bet on the number that never appeared, but he got a lot of money out of the other numbers that he found.

> "Kepler decided to go ahead because we demonstrated that there are plenty of other kinds of planets" **Didier Queloz**



Left: Queloz is chairman for the science team behind the ESA's CHEOPS mission

Right (top): Understanding other planetary systems has consequently changed our understanding of how our Solar System evolved

Right (bottom): Mayor present at the Nobel Prize Museum in Stockholm, Sweden

MM: The first people having really made the most precise measurements to search for exoplanets were two Canadian people, Gordon Walker and Bruce Campbell. It was very interesting to see that they were using the 3.6-metre (11.8-foot) telescope in Hawaii, as it was only able to obtain six to eight nights. So you see, it was extremely difficult to get measurements on that because this kind of programme was not considered a top priority. After, it changed completely, and I believe we never faced real difficulties of this kind.

Your discovery of a Jupiter-sized planet that only takes four days to orbit its star is something unimaginable if we thought about it in the context of our own Solar System. How do you think your discovery changed our understanding of planetary formation, and how can we apply that to the formation of our own Solar System?

MM: It's a very good question because it is important to remember that the reason for this kind of short-period planet was only existing as an interpretation. In the 1980s there was a paper by Peter Goldreich and Scott Tremaine announcing a theory that was discovered later called 'orbital migration'. If you have a young planet embedded in a disc of dust and gas, we have a very strong phenomena creating the migration of the planet towards the star, and it is explicitly written in the abstract that Jupiter was not born where it is today. But apparently no observer carefully read this paper, because the main focus of this paper was devoted to galaxy engulfment. When you have a small galaxy like one of the Magellanic Clouds and it is touching the Milky Way, it would be suffering exactly the same phenomena.

In fact the understanding of the short period of 51 Peg, it was already existing 15 years before. But nobody realised. Afterwards there were several papers by many other people having continuously studied this kind of problem, but it's very strange that nobody basically said, "Maybe it would be best to try and find this short-period object." And it's only after the discovery of 51 Peg people published a paper showing the link between these two kinds of approach.

DQ: That is the best summary by Michel. But it's clear that the reason before and after [the discovery of 51 Peg], where people were seeing planetary formation from a different angle. I mean it's always the same. You don't have to throw the theory away in the trash. But there was a really big missing piece. An interesting aspect which people are trying to explore right now is, what about the Solar System itself?

Shortly after the discovery of 51 Peg, people were starting to think about how maybe the Solar System has changed as well. People then came up with theories such as the 'grand tack' or 'late heavy bombardment' where there has been a restructure of the Solar System due to motions at the time of the formation of the system. I think that the concept right now, which is the system has moved around from its initial position, is fully accepted, and it was definitely 51 Peg that enforced this concept into the theory.

MM. After a few years just after the discovery of 51 Peg, it was a very important discovery for the diversity of systems. It has huge diversity with extremely short periods, strange organisation of the distances of planets and extremely elongated orbits. A lot of complexity was found compared to what we have in the Solar System.

Are there any missions or projects coming up that you will be keeping a very keen eye on in the field of exoplanetary research?

DQ: A project I was very keen to establish – which took me quite a long time to convince agencies and people to join in on – is to design what's called an experiment to find an 'Earth twin'. This is to build state-of-the-art equipment and then to dedicate a telescope for ten years to probe a limited number of stars. This is called the 'Terra Hunting Experiment'. That's something I was keen to start when I moved to Cambridge, and I created a dream team of people and universities around this project.

Now, of course, there are a lot of other big programmes that exist for which there is a lot of excitement around. One of them is the launch of the James Webb Space Telescope, because that will be a game changer in terms of the analysis and the study of an exoplanet's atmosphere. As well there will be the Extremely Large Telescope, when there will be a high-resolution spectrograph on it. And of course there is CHEOPS, which will be launched soon, and I'm very, very excited.

FutureTech

We explore some technology that could propel us into the future

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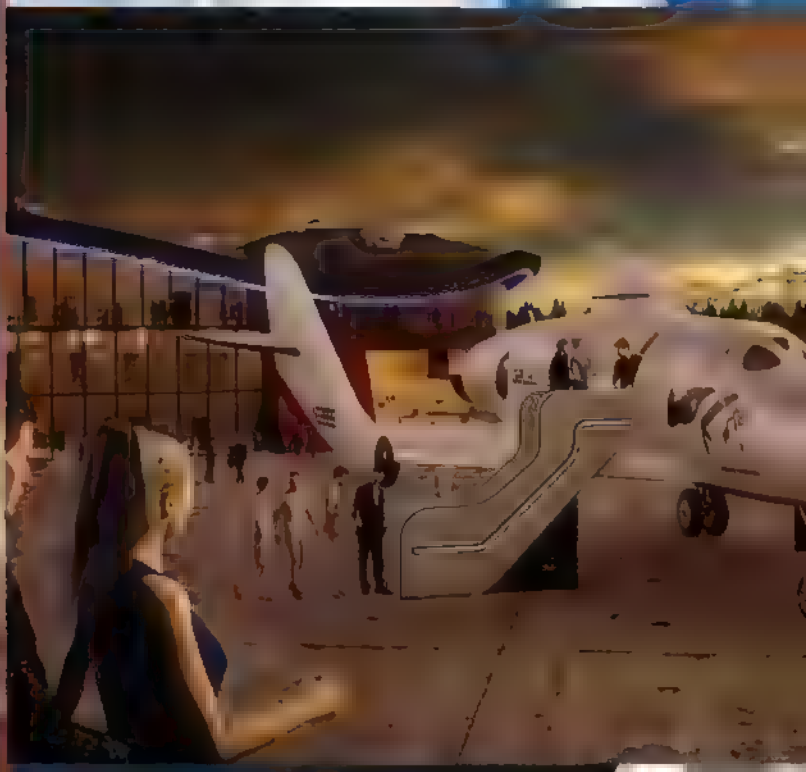
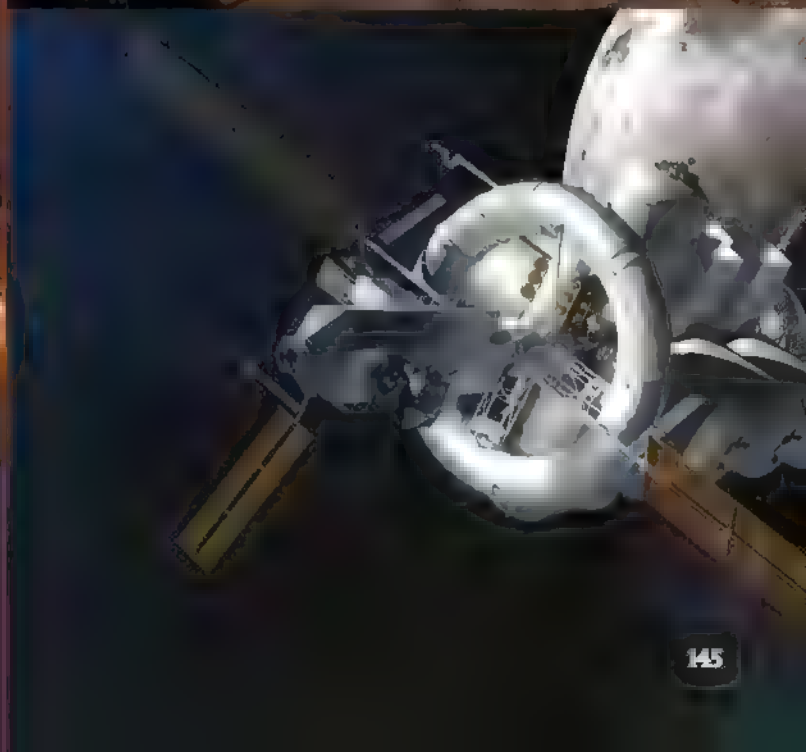
"We will be fully integrating space launches with Virgin Orbit into our everyday airline activities" MELISSA THORPE





THE VON BRAUN SPACE STATION

Bored of city breaks and cruises? 2025 could see the construction of the first hotel in low-Earth orbit

Maximum occupancy
The Von Braun Space Station will accommodate between 350 and 450 people, with a crew of around 100 included in that figure.

artificial gravity. Instead of having to be strapped to a wall to sleep in zero gravity, which is what astronauts on board the International Space Station (ISS) do at the moment, you'll have a comfy bed to lay on. There also won't be any zero-gravity-related complications when using the toilet. Alatorre has said in previous interviews that he hopes the Von Braun Space Station will be operational in 2025, and completed in 2027.

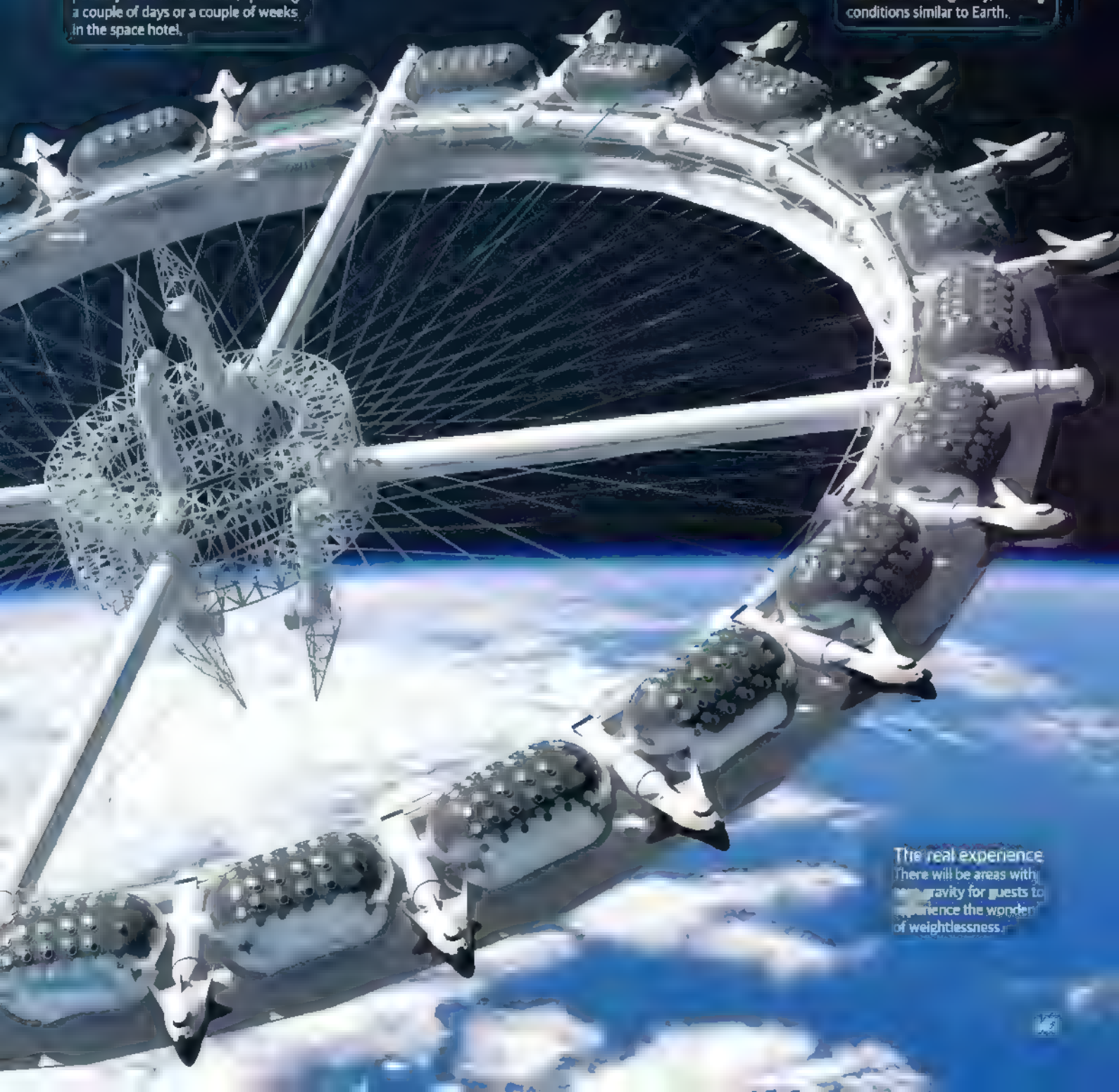
Alatorre has stated that the Gateway Foundation feels it now has the potential to make this dream a reality due to the recent successes of other commercial aerospace companies, such as SpaceX. Low-cost launches make space construction financially feasible, and by using the same technologies developed for previous space stations, there isn't the need to create anything new.

However, there are still plenty of hurdles to overcome before such a project can begin construction. For starters, there are consistent and extreme temperature changes for stations in orbit as the constant, rapid revolutions around Earth lead to them lying either in the dark and cold of Earth's shadow or in direct sunlight. The station's designers will need to carefully plan the pressurised modules to handle the constant temperature changes to ensure the guests are comfortable.

The creation of this space station holiday destination would mean that guests going into space aren't astronauts who have spent years undergoing intense training to live in space. Astronauts have also shown that the body can undergo changes living in reduced gravity, meaning there are definitely some serious health precautions to the general public that need to be considered before such a getaway can be planned.

Constant arrival
New guests could arrive once, or possibly even twice a week, spending a couple of days or a couple of weeks in the space hotel.

Creating gravity
A rotating-wheel space station induces artificial gravity, creating conditions similar to Earth.



The real experience
There will be areas with zero gravity for guests to experience the wonders of weightlessness.

THE RISE OF THE SPACEPORT

Increasing commercial space activity has called for more spaceports, and the world has answered

Reported by Lee Cavendish

Put yourself in the era of the 1950s and 1960s: space is a place exclusive to government agencies as the United States and the Soviet Union locked horns in the Space Race. Fast forward 50 years and space is now open to anyone and everyone, and commercial aerospace companies are making a real surge forward in making space tourism a real thing, no longer in the realm of science fiction.

Three major players in the game are SpaceX, Blue Origin and Virgin Galactic. All three are owned by their respective billionaire entrepreneurs Elon Musk, Jeff Bezos and Sir Richard Branson. These three companies are on the verge of offering flights into space for the average person - if they can afford the luxury - and the 2020s will undoubtedly see amazing milestones in this area. There are also many other aerospace companies around the world looking to capitalise on the commercial space industry, launching their own satellites into space without needing help from government rockets.

With this incredible increase in commercial activity in space, there has also been an increase in spaceports to accommodate such busy timetables. A spaceport isn't much different from an airport, but instead of putting things into the air, these ports are sending objects into space. There are two types:

a vertical launch, which launches a classic two- or three-stage rocket, or a horizontal launch, which sends a spacecraft up to an altitude of roughly

Space Center in Florida, as well as the Soviet Union's Kapustin Yar Cosmodrome and Baikonur Cosmodrome, now in Kazakhstan. Compare this to 2018, where there were 168 orbital

The United Kingdom is also now looking to create its first spaceports, with the introduction of a vertical launch spaceport in Sutherland, Scotland, and a horizontal launch spaceport in Cornwall, England. This development is stirring a lot of excitement around the country as it has great potential to improve the local economy and increase the national revenue from the space industry. "It is only recently that the demand for small satellite launches has been growing quickly. Five years ago the UK government recognised that the UK builds a large proportion of the world's small satellites, yet cannot launch them," Melissa Thorpe, head of engagement at Spaceport Cornwall, explains to **All About Space**. "The ability to have a sovereign launch capability and grasp the market will allow the UK to realise 10 per cent of the world's space economy. We will be providing a horizontal launch capability for the small satellite market with our partner Virgin Orbit, and we are in discussions with several other leading space companies for future projects."

But there is so much more to a spaceport than just its launch capability. As the former head of the Federal Aviation Administration's (FAA) commercial space office, George Nield, said: "Instead of just viewing spaceports as locations from which launches and reentries are conducted, I think it's also important to recognise that they can serve as focal points and technology hubs."

"How many spaceports do we need?" Nield continued. "As many as it takes to ensure our national security, to maintain technological leadership, enable international competitiveness and provide inspiration for students and development of our aerospace workforce."

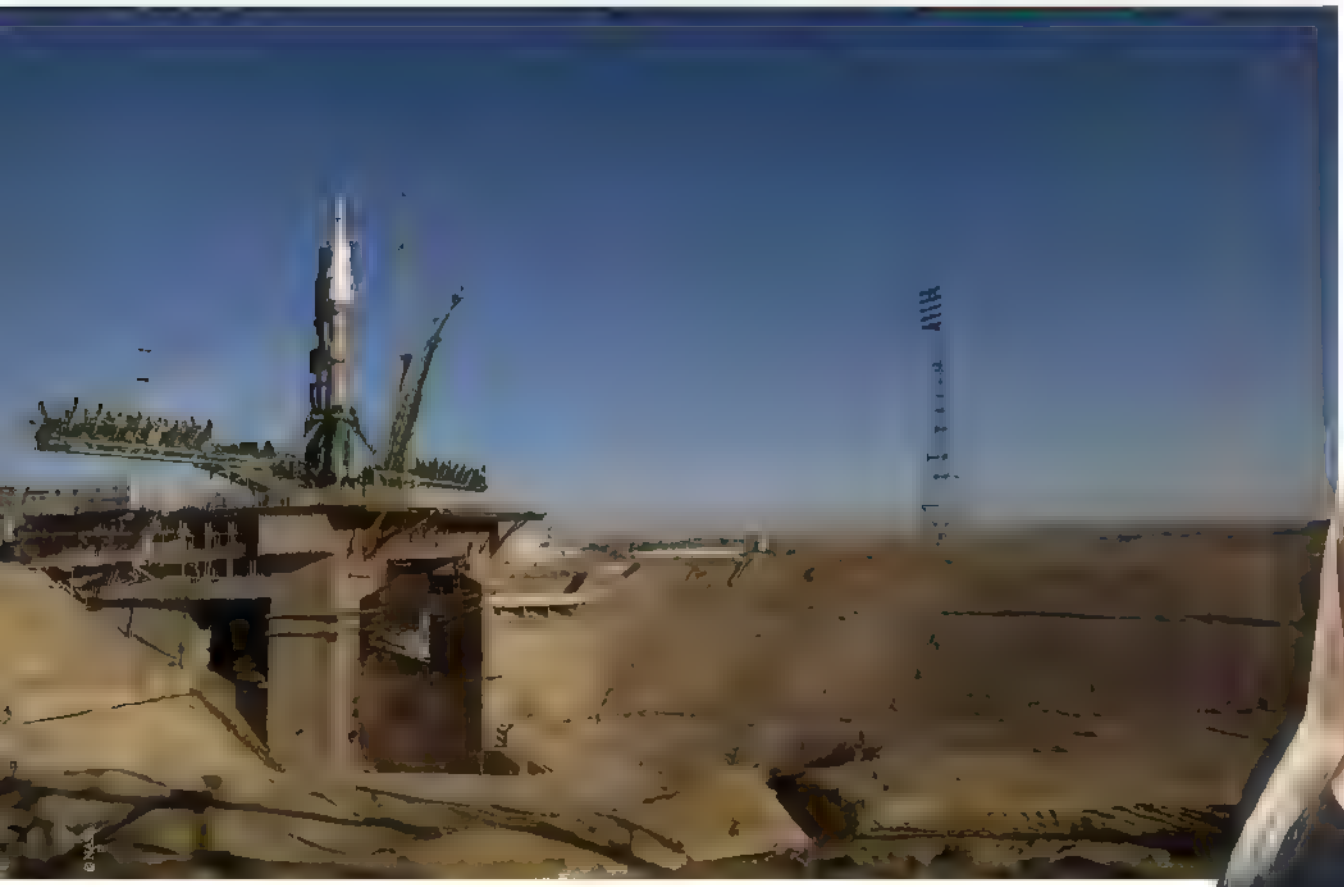

© NASA

NASA and Russian Roscosmos have been at the forefront of manned space exploration since the 1960s, having settled the Space Race with a continuous presence in low-Earth orbit on board the International Space Station (ISS) along with greater international collaboration. As of 2018 NASA has outlined that it wants to return to the Moon, sending the first woman and returning a man, with another eye on visiting Mars. NASA has to do this on a $22.6 billion (£16.9 billion) budget, which is only 0.48 per cent of the United States entire budget. With a plan like this constrained by tightened purse strings, the space agency has called for the intervention of private companies to take over presence in low-Earth orbit.

This call has been answered by multiple aerospace companies looking to make their presence known in space, and in doing so they are working hard to bring this experience to the people. One of the companies ready to make its mark in space is SpaceX, which has evolved remarkably under the leadership of Elon Musk. This company has formed and developed a great partnership with NASA through multiple cargo launches to the ISS using SpaceX's Falcon 9 reusable rockets. Boeing, another American aerospace company, is also going to send astronauts soon as part of NASA's Commercial Crew program.

SpaceX has performed a majority of its launches from the Kennedy Space Center but is in the process of building the SpaceX South Texas Launch Site at Boca Chica Village in Texas. Assuming SpaceX is granted a spaceport license by the FAA, the company could soon be launching its next-generation heavy-duty reusable rocket – the Starship. This spacecraft and booster rocket

> "The UK builds a large proportion of the world's small satellites, yet cannot launch them" **Melissa Thorpe**

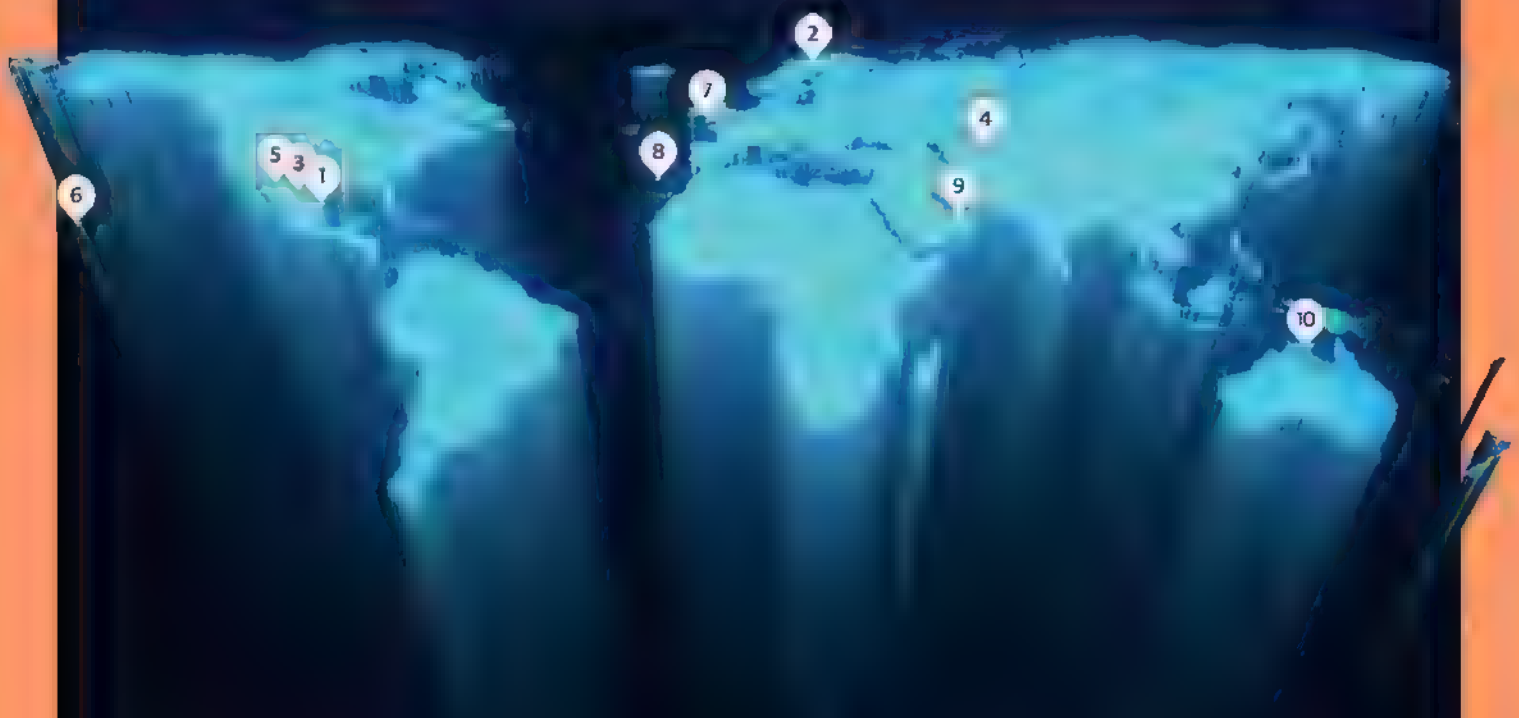


Above: Dennis Tito (left) was the first space tourist to fund his own spaceflight in 2001

Left: Baikonur Cosmodrome has been the home of all astronauts launching to the ISS since NASA's Space Shuttle retired

The present and future of spaceports

With the rise of space tourism and commercial spaceflight, spaceports are popping up all over the globe



SpaceX South Texas Launch Site, United States

1

Also known as the Boca Chica Launch Site, SpaceX has had great support from the Texas state government and will continue with the construction of the spaceport and apply for an FAA license upon completion.

Spaceport Sweden, Kiruna

2

Active in the development of commercial manned spaceflight since 2005, Sweden's contribution to the commercial space industry is its Spaceport Sweden, located in Kiruna in the Arctic Circle, which will hopefully accommodate Virgin Galactic.

Blue Origin West Texas Launch Site, United States

3

As New Shepard continues to climb to new heights, Blue Origin will use its FAA-licensed launch site in the West Texas plains to continue to test and improve the world's first fully reusable vertically launched space vehicle.

Baikonur Cosmodrome, Kazakhstan

4

This Russian-leased spaceport has been launching astronauts and tourists for decades now, being the launch site used to send astronauts to the ISS. Roscosmos will continue to launch from this spaceport in the foreseeable future.

Spaceport America, New Mexico, United States

5

The world's first spaceport built for purely commercial operations is the new home of Virgin Galactic, who has recently announced its 'Gateway to Space', a beautiful communal area customers will use prior to their spaceflight.

Hawaii Air and Space Port

6

Hawaii is looking to improve its economic diversity by introducing a spaceport at Kona International Airport, and it may introduce suborbital point-to-point flights to the mainland United States that will shorten journey times for island commuters.

Spaceport Cornwall, United Kingdom

7

Spaceport Cornwall will accommodate horizontal launches. It will start with Virgin Galactic's sister company Virgin Orbit launching small satellites. However, it will have great facilities to accommodate space tourism adventures.

Portugal Space, Santa Maria

8

Portugal looks to crown its newly formed national space agency with the country's first spaceport in the Azores, which may potentially be let out to space tourism companies such as Virgin Galactic and Sierra Nevada.

Al Ain Airport, United Arab Emirates

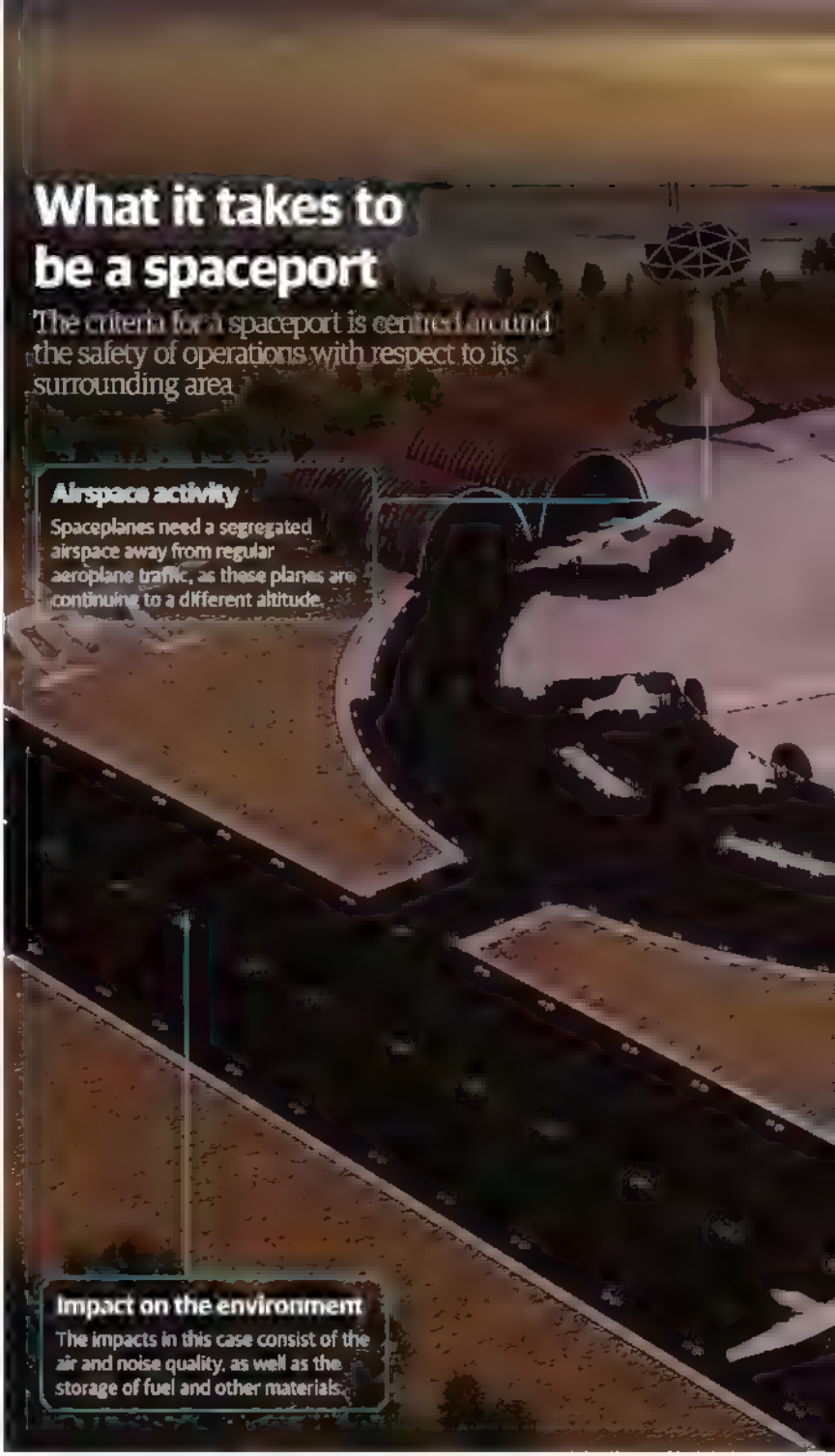
9

The UAE Space Agency has big plans for space exploration and space tourism in the coming years, and it will be looking to use Al Ain Airport in a partnership with Virgin Galactic to perform spaceflights.

Arnhem Space Centre, Australia

10

Equatorial Launch Australia (ELA) is looking to build and operate Australia's first commercial spaceport in the northern region of the country. This will allow orbital and suborbital access to space for the country.



combo is 50-metres (164-feet) tall and is capable of transporting passengers to the Moon and Mars

In September 2018, Musk announced that someone has already bought tickets to the Moon on board SpaceX's Starship. Japanese billionaire Yusaku Maezawa, founder of Zozotown, will take a translunar flight as early as 2023. Neither Musk or Maezawa revealed how much the flight cost, and all that was divulged was that Maezawa has already made a substantial downpayment

SpaceX also has plans to make Starship a point-to-point suborbital flight to destinations all around the world. In a promotional video posted by SpaceX in September 2017, it showed passengers boarding a Starship rocket that would take them from New York to Shanghai in just 39 minutes. In July 2019 it was also reported that the European Space Agency is drafting plans to start operating suborbital flights from Spaceport Cornwall that could start offering journeys from the UK to Australia that take just 90 minutes. This is a journey that would conventionally take roughly 20 hours by aeroplane

Nield has stated that these kinds of suborbital point-to-point flights should start with short distance journeys to nearby spaceports. But there needs to be a collective and overarching policy for everyone to adhere to. "We can articulate and document and then communicate this vision in a new policy" he said, pointing out that this whole process could lead to a new office of spaceports with the help of the FAA. "If we can get that up and running with the appropriate resources, staff and funding, that office could be a huge benefit in terms of being a focal point and an advocate"

Above: Virgin Galactic and Under Armour recently showcased the spacewear for private astronauts

Below right: SpaceX's Starship could provide travel to the Moon, Mars and other destinations

> "I think it's also important to recognise that spaceports can serve as focal points and technology hubs" George Nield

Blue Origin will offer a unique experience, as passengers are jettisoned to the edge of the Earth to gaze upon its awe-inspiring curvature for prices yet unknown. Jeff Bezos' team reached some major milestones during testing of the reusable, vertically launched New Shepard rocket-capsule pairing in 2019 at its FAA licensed West Texas suborbital test launch site. On 2 May 2019 New Shepard was jettisoned to a personal-record altitude of 106 kilometres (66 miles) while carrying 38 science experiments for various organisations, including NASA. After the launch the rocket made a safe vertical landing and the capsule was gently placed on the West Texas plains. When it is fully operational, this unique 18-metre (60-foot) rocket will take six people beyond the imaginary line of space known as the Kármán line, which lies at 100 kilometres (62 miles) in altitude. During this 11-minute vertical flight, tourists will be able to experience weightlessness for four of those minutes. After the event is concluded, the entire set-up can be refuelled, reconfigured and reused – and that will make the cost a lot cheaper

The third billionaire space-tourism enthusiast is Sir Richard Branson with his Virgin Galactic. This offers an entirely different option of space tourism to SpaceX and Blue Origin. Virgin Galactic aims to take its passengers to space using the

Prime location

The spaceport needs to be located away from densely populated areas. Normally they are situated on a coastal area in case of explosions or falling debris. It needs to be within travelling distance for employees.

Favourable weather

This is more of a lottery, but it doesn't hurt chances in choosing a place that experiences better weather.

Runway requirements

In order to conduct horizontal launches, a spaceport is required to have a runway extending up to roughly three kilometres (1.9 miles).

What to expect when flying

Departure

Horizontal and vertical launches are very different. Horizontal launches will be flown to high altitudes before detaching from the aircraft carrier and continuing the journey beyond the Kármán line. Vertical launches will be the same as astronauts have been experiencing for decades, with the intense burst of power shooting craft towards the heavens. The launch could arguably be the most enjoyable part for thrill-seekers.

Inflight experience

Virgin Galactic and Blue Origin will offer the views of space, the curvature of the Earth and weightlessness for about six and four minutes respectively. SpaceX's space tourism trip to the Moon is an endeavour that takes days. This prolonged visit to space will have effects on the human body and its vestibular and proprioceptive systems, leading to feelings of nausea and disorientation.

Landing

Horizontal landings wouldn't be too dissimilar to an aeroplane landing on a runway. However, a vertical launch would lead to being parachuted down in your capsule into a desert, where you'd be collected and returned.

Arrival

Suborbital flights to the same destination don't require a passport, as you're not crossing any borders. However, point-to-point spaceflights will require your passport, for example on SpaceX's New York to Shanghai spaceflight. Returning from the ISS or the Moon may require you to fill out a customs declaration form, as even the Apollo astronauts had to do this.

reusable SpaceShipTwo spaceflight system, with the current operational model referred to as VSS Unity. This craft performs a horizontal launch from Virgin's spaceport using a custom-built aircraft carrier called WhiteKnightTwo. When the launch vehicle reaches an altitude of 15 kilometres (nine miles), SpaceShipTwo will detach and finish off the journey beyond the Kármán line.

This adventure has appealed to plenty of people already, and reportedly over 600 people from 60 countries have already placed deposits to be one of the first of Branson's high-flyers. The fare for such an adventure is to be within the region of £200,000 ($250,000) for the 90-minute spaceflight. It's a hefty price, but you could find yourself sitting next to some celebrities that have already bought their tickets, such as the

How space affects both men and women

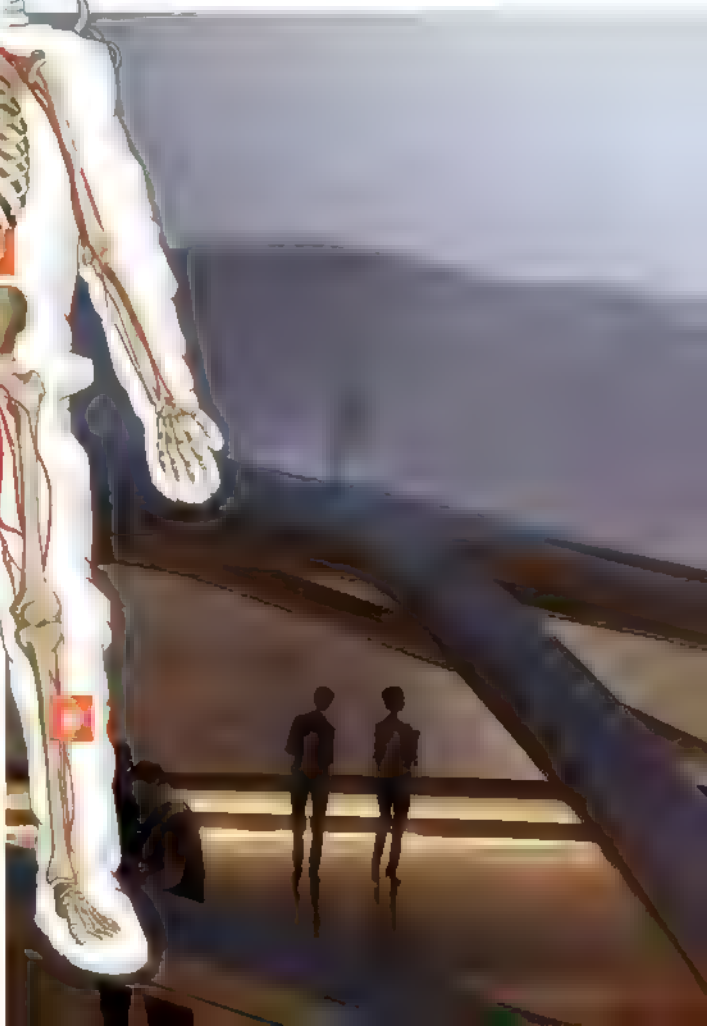
Below: Elon Musk and SpaceX want to create spaceships that can make humans an interplanetary race, with a base on Mars

likes of Leonardo DiCaprio, Tom Hanks, Justin Bieber and many others.

Virgin Galactic has had highs and lows during testing. A chasmic depth was the crash of VSS Unity's predecessor, VSS Enterprise, in the Mojave Desert, California, on 31 October 2014. This disaster claimed the life of co-pilot Michael Alsbury, while pilot Peter Siebold was severely injured. Much to its credit, Virgin Galactic regrouped and has since conducted several successful test flights - the most recent being on 22 February 2019. This test saw three astronauts, including the first ever passenger, soar to an altitude of 90 kilometres (56 miles).

Virgin Galactic recently relocated its employees and its testing and commercial operations from the Mojave Air and Space Port, California, to a cosy spot known as Spaceport America, the world's first fully commercial spaceport in the desert basin of New Mexico. This is a huge step forward for the company's plans to dominate space tourism, as this spaceport will be the hub for its operations. Virgin has recently announced its 'Gateway to Space', a swanky communal area for paying customers, a little like an airport lounge. It won't be long now before customers are strolling through spaceports in the same relaxed and calm manner as they would go through an airport, grabbing a coffee while they wait for their flight.

This could be the case for many horizontal launches, as Thorpe explains. "A horizontal-launch spaceport, such as ours, can operate from an existing airport - in our case Cornwall Airport



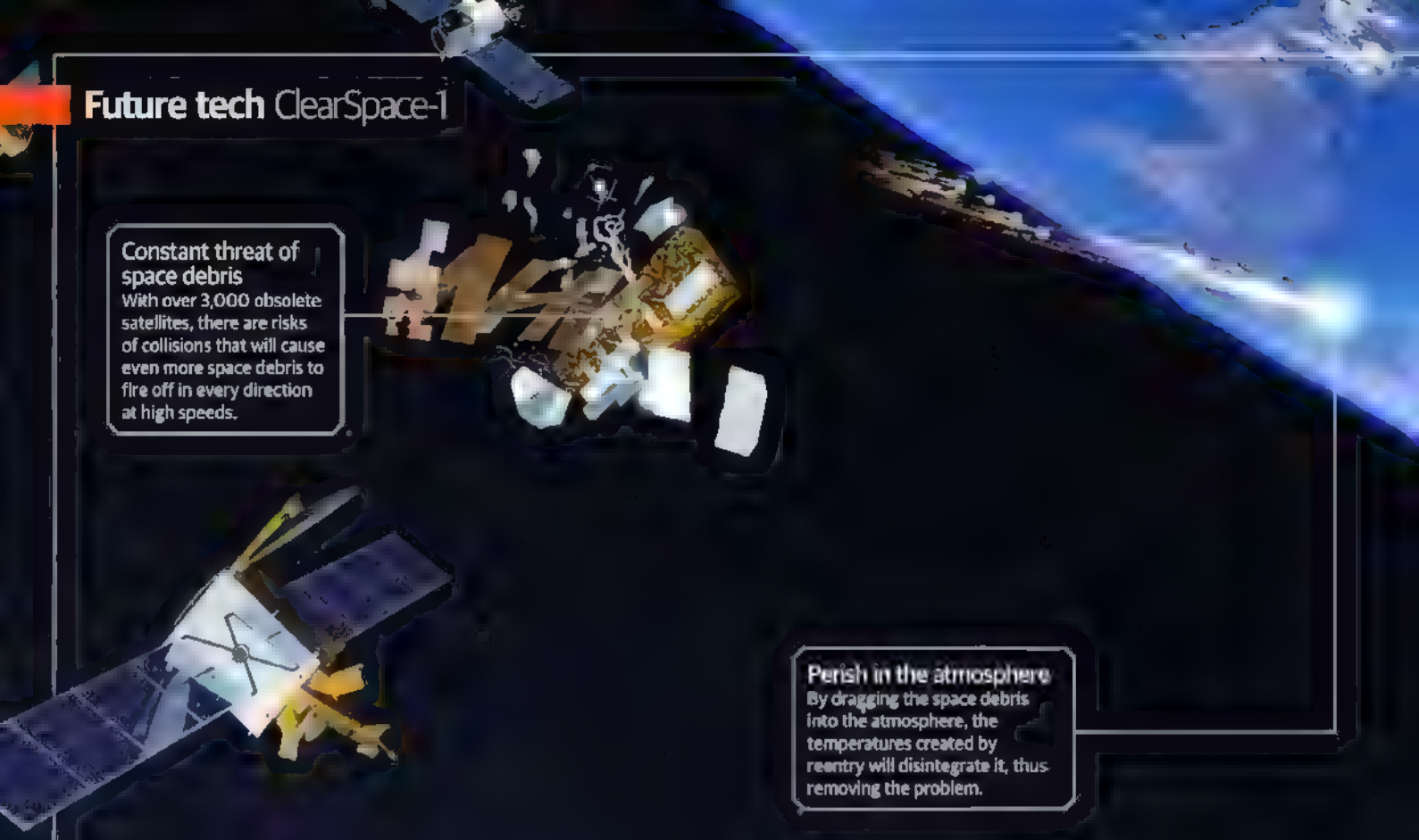
Newquay A spaceport requires separate legislation to allow flights and launches. This secondary legislation for spaceflight will give us the regulations required to launch satellites in the UK We are an operational commercial airport, and we will be fully integrating space launches with Virgin Orbit into our everyday airline activities. We will be one of the only places in the world to do this."

Space tourism is not a new concept. The Russian space agency Roscosmos, in tandem with the American space tourism company Space Adventures, has been sending wealthier members of the public into space since 2001. The first one to exploit the market was American engineer and entrepreneur Dennis Tito. He had a luxurious week-long stay on board the ISS, which reportedly set him back £15 million ($20 million). Since then several super-rich clients have spent tens of millions to go to the ISS, and are continuing to do so, as two more tourists are due to launch in 2021. All of these missions were launched - and will continue to be launched - from the Baikonur Cosmodrome aboard a Soyuz rocket. An extreme percentage of the fee would likely go to launch costs, as the Soyuz rockets are not reusable.

The vast expense of such an adventure is the main reason why space tourism was deemed unreachable. But with this wave of emphasis on reusability and a string of promising tests performed by the aforementioned aerospace companies, other industries and organisations around the world are looking to become a part of this rapidly growing industry.

Expanding horizons beyond the constraints of the United States and Russia, spaceports are being lined up around the world. Europe could see the advent of spaceports in the United Kingdom, Sweden and Portugal. Even Australia and Asia are getting their own gateways to space in order to exploit this expanding market. In fact, in 2017 the UK House of Commons prepared a 'Space Sector Report' that stated that the current global space economy market is worth somewhere between £155 and £190 billion (approximately $200 and $250 billion), and is expected to reach £400 billion (around $530 billion) by 2030. This is over double the value in just ten years' time. With companies and organisations all over the world investing in this growing market, it is likely that space tourism could soon be a worldwide phenomenon.

"We will be fully integrating space launches with Virgin Orbit into our everyday airline activities" **Melissa Thorpe**



Constant threat of space debris
With over 3,000 obsolete satellites, there are risks of collisions that will cause even more space debris to fire off in every direction at high speeds.

Perish in the atmosphere
By dragging the space debris into the atmosphere, the temperatures created by reentry will disintegrate it, thus removing the problem.

CLEARSPACE-1 THE KAMIKAZE SPACE CLEANER

This European mission will be purging low-Earth orbit with a space-debris removal plan for 2025

The European Space Agency (ESA) has recently commissioned its first mission to begin the clean up of space debris. Space debris has become an increasing problem with the ever-growing population of satellites in low-Earth orbit, and there are currently limited efforts to clean the mechanical mess that is left behind in space. This new European mission will launch an experimental, four-armed robot named ClearSpace-1 in 2025 to see if this could be the answer for a large-scale cosmic clean-up. If successful, this robot could soon be hugging pieces of space junk and performing a kamikaze dive into Earth's atmosphere, where they will both burn up upon reentry.

Material drifts around in low-Earth orbit, left over from rockets, space stations and satellites. In fact, there are nearly 2,000 live satellites currently parked in low-Earth orbit, and over 3,000 defunct ones. This is the space equivalent of having 3,000 cars break down and then just leaving them on the road. It would likely cause an accident. The International Space Station in particular is constantly at risk. Its windows could be pierced with a piece of space junk travelling

The chaser
The 'chaser' is ClearSpace-1's four-armed robot that is tasked with catching space debris and dragging it back to Earth.

Vespa
This particular piece of European space junk was chosen because of its shape and sturdiness, ensuring that it won't break up after being seized.

at an average speed of around 36,000 kilometres (22,370 miles) per hour. This puts the lives of astronauts at risk.

"The space debris issue is more pressing than ever before," says Luc Piguet, founder and CEO of ClearSpace, the Swiss junk-removal start-up partnering with the ESA. "Today we have nearly 2,000 live satellites in space and more than 3,000 failed ones. And in the coming years the number of satellites will increase by an order of magnitude, with multiple mega-constellations made up of hundreds or even thousands of satellites planned for low-Earth orbit."

This mission, scheduled to launch in 2025, will involve launching the ClearSpace-1 'chaser' satellite into low-Earth orbit, where it will rendezvous with a piece of space debris named Vespa. The defunct junk's full name is the 'Vega Secondary Payload Adapter', and it is the 100-kilogram (220-pound) upper stage of a Vega rocket, left over from a spaceflight in 2013 and still orbiting about 800 kilometres (500 miles) above Earth's surface.

After the chaser latches onto Vespa, which is a similar size to a small satellite, it will undergo a controlled reentry into the atmosphere of Earth and will finish in a blaze of glory under the supervision of the ESA.

As there is so much debris to clean up, this mission alone will surely not be enough. Even if all satellite launches were to stop tomorrow, the amount of space debris would still increase due to collisions and the resulting cascade effect. ClearSpace-1 is certainly a step in the right direction, however, as it will remove a larger piece of debris while simultaneously providing vital information about the technologies and techniques involved – and needed – for such an operation.

NAUTILUS-X

The artificial-gravity spacecraft that could take humans to the Moon and beyond

When it comes to manned missions into deep space there is no shortage of proposals. People have dreamt up spacecraft with various fantastical elements, from futuristic propulsion engines to somewhat ambitious aesthetic designs, but one proposal that warrants a serious glance is Nautilus-X. It's a spacecraft that builds largely on existing technology to make human exploration of the Solar System a realistic possibility, and at a reasonable price too.

Drawn up by NASA engineers Mark Holderman and Edward Henderson, the name stands for Non-Atmospheric Universal Transport Intended for Lengthy United States Exploration. Nautilus-X would be capable of supporting a crew of six for missions lasting from one month to two years. Although it might look like a mini space station, the whole thing is designed to be able to travel throughout the Solar System, be it near the Moon or Mars. Although incapable of descending to the surface of another world itself, it has docking ports to which landing craft can be attached.

The design of the spacecraft means that it could remain in space for many years, with several different crews utilising it. For example, one crew could travel to Nautilus-X in an Orion spacecraft and then take the entire spacecraft onwards to Mars for a mission lasting up to a year. They would then return in Nautilus-X at the conclusion of the mission and leave the spacecraft near Earth orbit, ready and waiting for another crew, while they travel back to the surface of Earth in their Orion capsule.

Such an implementation would allow multiple rotating crews to make use of the spacecraft on a variety of missions. Solar panels would make the station almost entirely self-sustainable, while onboard farms could provide astronauts with food. At the outset of a mission, however, it's likely astronauts would need to bring some supplies with them, perhaps on a separate spacecraft such as SpaceX's Dragon.

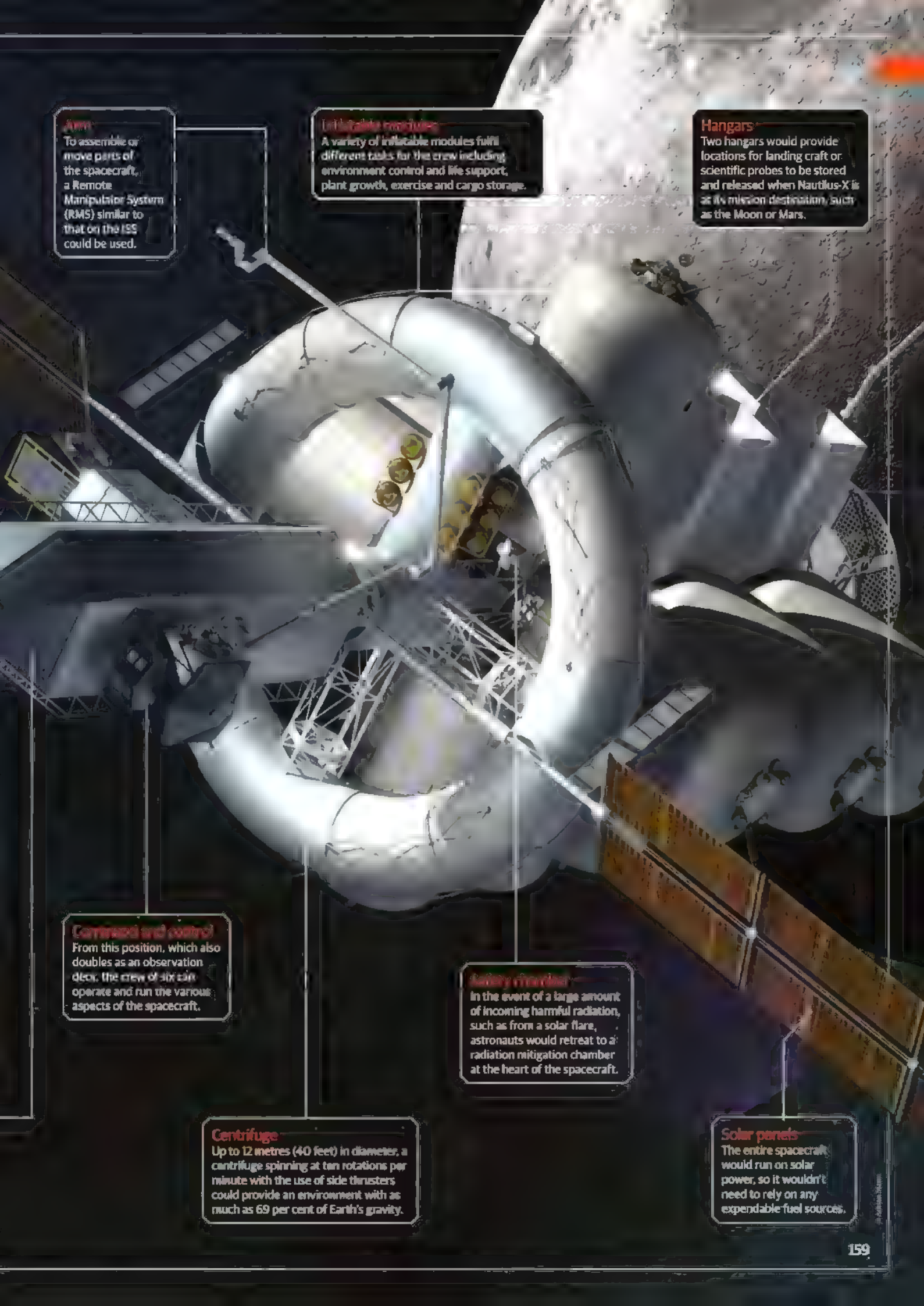
Another key feature of Nautilus-X is the centrifuge. It is well documented that prolonged exposure to space can have a debilitating effect on an astronaut's health, in particular their muscle and bone strength. It is estimated that as much as two per cent of bone mass is lost for every month an astronaut is weightless in space, so providing an artificial-gravity environment could be essential for long-term exploration missions. The centrifuge on Nautilus-X would provide between 0.51 and 0.89 of Earth's gravity, allowing astronauts to recuperate bone mass they may have lost while on other parts of the spacecraft or outside on a mission. Such a centrifuge had been suggested as an additional module for the International Space Station to test the technology, but unfortunately that now seems to be on hold due to budgets.

On the subject of money, Nautilus-X carries with it a rather alluring price tag. The brains behind the project estimate it would cost around $3.7 billion (£2.3 billion) – not even double the price of NASA's Curiosity rover – while development could be completed in just over five years. Such figures are attractive, especially for the money-conscious top dogs at NASA, so there is a chance that after further research this spacecraft may come to fruition.

So when could we expect to see work on Nautilus-X begin? At the moment NASA's manned exploration funding is tied up in a number of projects, namely Orion, Commercial Crew Development – which includes funding for SpaceX, Boeing and Sierra Nevada Corporation's upcoming manned vehicles – the ISS and the Space Launch System heavy-lift rocket. The latter would be essential for launching and assembling the various components of this spacecraft in Earth orbit. Whether we will ever see Nautilus-X fly is up for debate, but it's good to know that NASA has a sound proposal for a deep-space exploration vehicle if it ever decides to go down that route.

Docking port
NASA's Orion spacecraft – and perhaps some commercial vehicles as well – will be able to take astronauts to and from Nautilus-X by docking here.

Corridor
The main corridor would measure 6.5 metres (21.3 feet) wide and 14 metres (46 feet) long.


Arm
To assemble or move parts of the spacecraft, a Remote Manipulator System (RMS) similar to that on the ISS could be used.
Inflatable modules
A variety of inflatable modules fulfil different tasks for the crew including environment control and life support, plant growth, exercise and cargo storage.
Hangars
Two hangars would provide locations for landing craft or scientific probes to be stored and released when Nautilus-X is at its mission destination, such as the Moon or Mars.
Command and control
From this position, which also doubles as an observation deck, the crew of six can operate and run the various aspects of the spacecraft.
Safety module
In the event of a large amount of incoming harmful radiation, such as from a solar flare, astronauts would retreat to a radiation mitigation chamber at the heart of the spacecraft.
Centrifuge
Up to 12 metres (40 feet) in diameter, a centrifuge spinning at ten rotations per minute with the use of side thrusters could provide an environment with as much as 69 per cent of Earth's gravity.
Solar panels
The entire spacecraft would run on solar power, so it wouldn't need to rely on any expendable fuel sources.

INTERSTELLAR RAMJET

Travelling between stars takes a lot of energy, but we might be able to pick some up on our way through space

The trouble with rockets is that you have to pack everything before you go. While earthly modes of transport all work within their environment, shooting around air or water or rolling along a surface, rockets must carry whatever they are going to shoot out the back – reactive mass – with them. This effect is exacerbated because the reactive mass you'll be using at the end of the flight is just dead weight at the start. So you need even more mass and energy at the start just to lift the mass and energy you will need later on. This is why it is so challenging and expensive to get into space. Rockets are so big compared to the payloads they launch because they need to be more than 90 per cent full of propellants at take off.

Once you're in space you have more options: craft don't need to be aerodynamic and the engines don't need to support a craft against gravity, so a small thrust over a long time is equivalent to a large one over a short time. However, if we want the space travel of fiction, to voyage across the stars to find other planets and life, the challenge gets even greater.

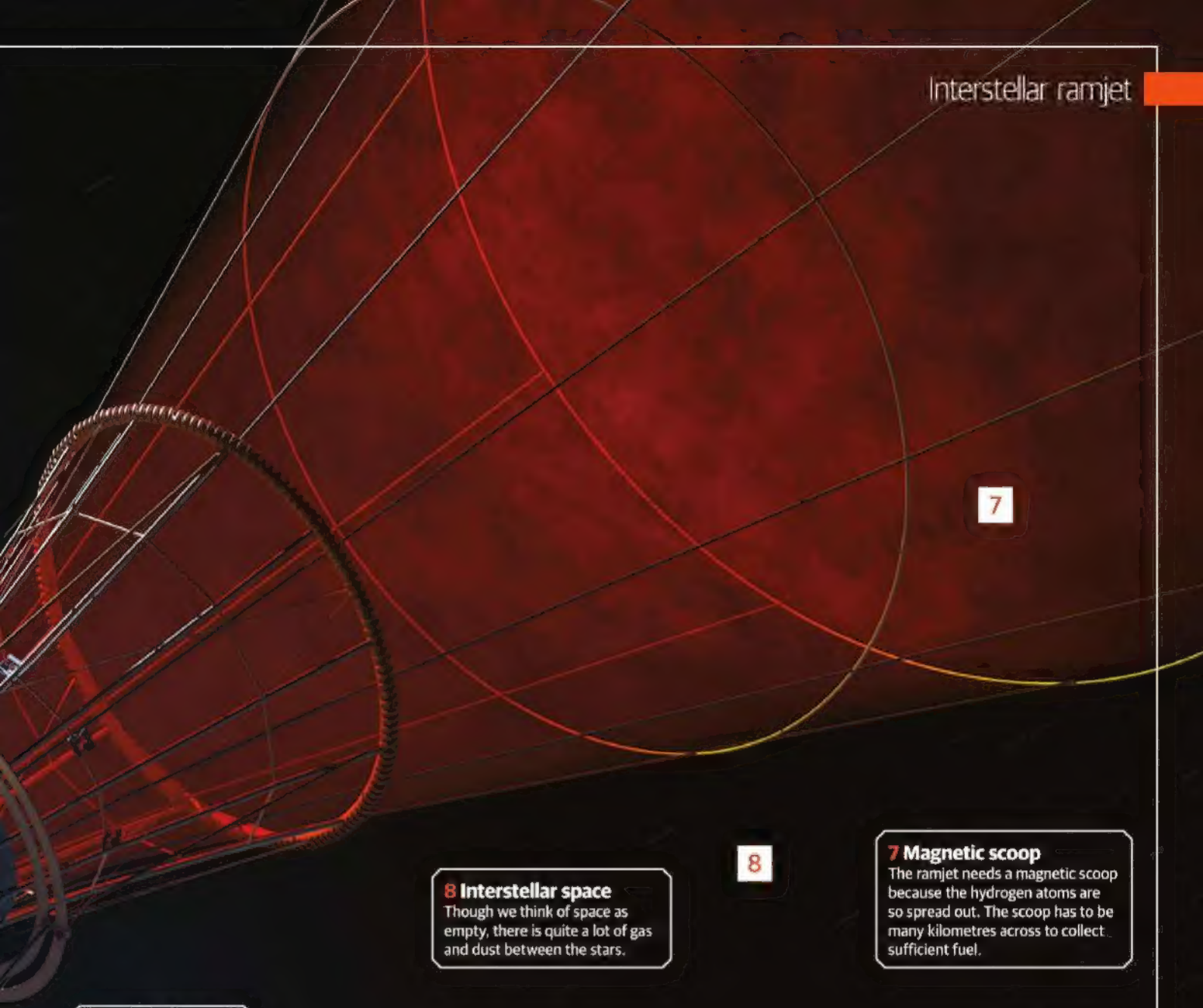
Proxima Centauri, the nearest star beyond the Sun, is 4.2 light years away, so traditional rockets would take thousands of years to get there. Worse still, if we are to approach light speed to minimise the travel time we have to drag ...

1 Fusion reactor
The hydrogen would be used to fuel a fusion reactor which would fuse hydrogen into helium, releasing a tremendous amount of heat energy.

2 Exhaust
The ramjet produces forward thrust by directing the ions produced from fusion out of the exhaust at a high velocity.

3 Fissionless
Current nuclear technology uses fission, where heavy atoms like uranium are split to release energy. But this does leave behind long-lived nuclear waste.

4 Nuclear fusion
The ramjet uses nuclear fusion. This releases energy by combining light atoms into heavier ones. It is cleaner and more powerful, but more difficult to achieve.



7 Magnetic scoop
The ramjet needs a magnetic scoop because the hydrogen atoms are so spread out. The scoop has to be many kilometres across to collect sufficient fuel.

8 Interstellar space
Though we think of space as empty, there is quite a lot of gas and dust between the stars.

6 Thermal and radiation shield
Fusion does not produce the same radioactive waste as fission, but when running on hydrogen the crew would need protection from neutrons and the exhaust heat.

5 Fuel tanks
The spacecraft needs to be able to run the reactor to power its systems, including the scoop, from a standstill. It would probably use deuterium, an easier fuel to fuse.

more propellant up to super-high speeds. As a result the Daedalus fusion-powered interstellar probe concept would stand nearly as tall as the Empire State Building and weigh 54,000 tonnes - 50,000 tonnes being propellant. But space isn't as empty as it appears, so what if we could make use of the resources already out there?

In 1960 nuclear physicist Robert Bussard proposed such a system: the Bussard ramjet. A ramjet is an engine that uses its forward speed to ram air into the engine, instead of the fan blades seen on jet engines. With the Bussard ramjet a craft would be initially set moving by a fusion-powered rocket using internal fuel, and then it would generate a huge funnel-shaped magnetic field. This could collect the free hydrogen molecules that float around in interstellar space and duct them back to the spaceship. Once collected the hydrogen molecules could be used as fuel for a fusion-powered rocket.

Nuclear fusion is the most powerful reaction we have available from ordinary matter. Current nuclear power stations use nuclear fission where energy is released by splitting heavy atoms, but in nuclear fusion energy is released by combining light atoms, which is cleaner and more powerful. The hydrogen molecules would be fused together, producing a hot jet of helium gas to push the spacecraft along while it collects more fuel.

There are challenges of course: the scoop would have to gather one trillion cubic kilometres (240 billion cubic miles) of space to pick up one kilogram (2.2 pounds) of hydrogen. Scooping up the hydrogen may create more drag than the engine can overcome, and hydrogen itself is not easy to fuse. Some studies have suggested it might be better to just use the interstellar hydrogen as a reactive mass, heated up by a separately fuelled fusion reactor.

Though the Bussard ramjet is still a theoretical concept, it has already had a cultural impact as the 'Bussard Ramscoop' on the front of the Starship Enterprise in *Star Trek*.

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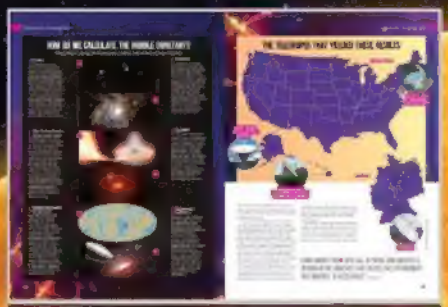

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